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Sub-second Temporal Processing:

Effects of Modality and Spatial Change on Brief Visual and Auditory Time Judgments

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Declaration

I hereby declare that this thesis is of my own composition, and it contains no material previously submitted for the award of any other degree. The work reported in this thesis has been executed by my self, except where due acknowledgement is made in the text.

Chrysoula Retsa

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ABSTRACT

The present thesis set out to investigate how sensory modality and spatial presentation influence visual and auditory duration judgments in the millisecond range. The effects of modality and spatial location were explored by considering right and left side presentations of mixed or blocked visual and auditory stimuli.

Several studies have shown that perceived duration of a stimulus can be affected by various extra-temporal factors such as modality and spatial position. Auditory stimuli lead to more precise duration judgments than visual stimuli and often last subjectively longer than visual stimuli of equal duration. The circumstances under which these modality differences occur are not clear yet. Recent studies indicated an interaction between temporal and spatial processing. Overestimation of durations was associated with right side presentation of visual stimuli, underestimation with left side presentation. However, the effect of spatial presentation has not been explored in the auditory temporal judgments. Furthermore, there is a debate concerning the mechanisms underlying processing of visual and auditory intervals with some researchers supporting the view that there is a central, amodal temporal mechanism and others arguing in favour of distinct, modality specific temporal mechanisms. The above issues were examined in a series of experiments using the duration discrimination paradigm. Processing demands where

varied between experiments by varying the number of stimuli positions and the way that different modality trials were presented (mixed or blocked).

Across all experiments we found no effect of location either in visual or auditory domain. However, in experiments in which different modality trials were intermixed, participants in the visual versions of the task tended to overestimate durations of comparison stimuli that were presented at different locations to the standard stimuli. In such conditions, visual stimuli were also judged to be longer than the auditory. However, when the location of the comparison stimulus was at the same side as the standard a reverse effect was observed. These findings call into question an influence of the position per se on temporal judgments as the visual duration judgments were affected rather by the change of the location. Auditory judgments were not affected by location manipulations, suggesting that different mechanisms might underlie visual and auditory temporal processing. Based on these results, we propose the existence of an error-correction mechanism, according to which a specific duration is added in order to compensate for the loss of time caused by spatial attention shifts. This mechanism is revealed under some circumstances (such as mixed modality) where it is over-activated, resulting into a systematic bias.

This work has important implications for the contemporary research in time perception as it is shedding new light on the possible ways that a unified experience of timing arises from modally and spatially specific temporal mechanisms.

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Chapter 1 –

INTRODUCTION PART I:

GENERAL

1.1 A Brief History of the Research on Time Perception

Time perception is a fundamental aspect of cognition. Every stimulus we perceive and every action that we take has a temporal dimension (Eagleman, Tse, Buonomano, Janssen, Nobre & Holcombe, 2005). Relatively accurate timing is essential in both the discrimination of different stimuli and the generation of coordinated motor responses (Karmarkar, & Buonomano, 2007). Temporal processing is immensely important for everyday functioning, as it is involved in most activities, such as crossing the street (since we need to predict when the light is going to turn red), driving a car, speaking or determining causality etc. Even reaching for an object requires a specific temporal pattern of activity among the muscles of the shoulder, the arm and the wrist. As time is ubiquitous in behaviour and everyday functioning, a broad variety of research in various aspects of temporal processing has been conducted involving behavioural and psychophysical studies in normal participants as well as neuroimaging and neuropsychological studies (Grondin, 2010).

1.1.1 Vierordt's law

One of the first reports of the experimental study of the perception of time occurred early in the history of experimental Psychology. "Der Zeitsinn" - "The experimental

study of the time sense" - was published in Germany by Karl Vierordt in 1868 (Leujeune, & Wearden, 2009). The main contribution of his psychophysical research on time perception is known as "Vierordt's Law". According to this law, short durations are judged as longer than they are, and longer durations are judged as shorter. There is an indifference point where durations can be judged veridically, which can be found somewhere in the duration range between the two extremes. Some of the ideas that were mentioned in Vierordt's book are pertinent to contemporary research, such as the effect of attention and modality or the difference between filled and empty durations. It has to be noted that Vierordt was possibly the first – earlier even than Guyau (1890) – to acknowledge that hearing is the most privileged modality for timing.

1.1.2 Weber's law

In addition to time specific laws – like Vierordt's law – it seems that duration perception also conforms to more generic laws, which apply in several sensory stimuli features. A ubiquitous finding in the timing literature is that time estimations, like most sensory dimensions, adhere to Weber's law: "constancy of the coefficient of variation" (Wearden & Bray, 2001). According to Weber's law, the magnitude of the smallest noticeable difference is proportional to the magnitude of the standard stimulus. More specifically, timing behaviour exhibits "scalar variability" which means that participants' responses are normally distributed (Buhusi & Meck, 2005). This scalar property in temporal behaviour has been found to apply not only to psychophysical performance but also to neural activation. For example, a relatively recent ERP study suggested that both adults and 10 months old infants' brain

responses showed this scalar property (Brannon, Libertus, Meck & Wooldorff, 2008).

Despite, the importance of the temporal processing in cognition and although research in the field of time perception has increased over recent decades, still the mechanisms underlying temporal processing and neurocognitive encoding of duration, are subjects of debate. Unlike visual, auditory, tactile and olfactory senses, there is no specific sensory organ to perceive and encode duration per se. Durations can actually be estimated both in and across modalities (Mamassian & Landy, 2010). Furthermore, the perceived duration of a stimulus is usually different to its physical duration as many factors, including physical characteristics of the stimuli as well as the state of the subjects, can interfere with or modulate the temporal perception.

1.2 Dissociations in Temporal Processing and their General Neural Correlates

Temporal processing is complicated and does not engage a unitary mechanism in the brain. The duration range, the nature of the time task and the sensory modality of the stimulus to be timed have been associated with different patterns of brain activation during temporal tasks.

1.2.1 Dissociation between duration ranges

It has been proposed that mechanisms involving different brain regions are engaged in processing events occurring over different time scales. More specifically, temporal processing has been broadly categorized into the following time scales: circadian

rhythms, interval timing (second to minutes range), millisecond timing, and microsecond timing (Koch, Oliveri & Caltagirone, 2009). Circadian rhythms operate over the twenty-four hour cycle of light and dark. This system deals with the control of sleep and wakefulness stages as well as with metabolic rhythm. The suprachiasmatic nucleus of the hypothalamus seems to be the centre of the circadian rhythms in the brain (Buhusi & Meck, 2005). Sound localization involves microsecond timing. Although the neural mechanisms in the shortest (microsecond) and the longest (circadian rhythms) ranges are fairly well established, and appear to be entirely distinct, the mechanisms underlying the intermediate ranges are far from certain (Buonomano, Bramen & Khodadadifar, 2009).

Interval timing, which deals with **suprasecond durations**, is more commonly associated with learned behaviours and is crucial for decision-making. M**illisecond** timing is important for motor control, speech generation, musical performance etc. In the present thesis we focus on timing mechanisms that underlie judgments at the millisecond time scale. A few studies have shown evidence that different temporal systems are being implicated in the subsecond and suprasecond ranges (Lewis & Miall, 2003; Ivry & Spencer, 2004). Timing in the millisecond range has been characterised as automatic and is more likely to recruit circuits within the motor system. Frequent activity at the supplementary motor area (SMA), the sensorimotor cortex, the right cerebellum and the lateral premotor cortex (PMC) have been associated with temporal tasks in the millisecond range. Superior temporal lobe (part of the auditory cortex) activity has been also reported by some studies in this duration range even in tasks where auditory stimuli are not involved. This activity

has been attributed to the use of auditory imagery during temporal tasks in the automatic range (Lewis & Miall, 2003).

Timing in the suprasecond range on the other hand is thought to be cognitively controlled, and is more likely to draw upon multipurpose circuits, particularly those associated with attention and working memory. This system seems to engage prefrontal and parietal cortices, as well as involving activation of the basal ganglia (Buhusi & Meck, 2005). More specifically, activation has been reported in the dorsolateral prefrontal cortex (DLPFC), an area which is also known for involvement in working memory processing. Furthermore, activation of the intraparietal sulcus and inferior parietal lobe, which are also associated with attention processing, has been observed in connection with temporal tasks in the suprasecond range (Lewis & Miall, 2003).

1.2.2 Automatic versus cognitive controlled timing

This dissociation between automatic and cognitive controlled timing systems is not solely based on the duration range of the temporal task. Rather, it is usually a combination of task characteristics that leads to the above distinction; apart from the duration, the use of movement and the continuity of the task play an important role. Thus, tasks that are usually included in the automatic timing system are involving continuous and predictable measurements of subsecond intervals and are defined by movement. Tasks with the opposing features are categorized as cognitive controlled (Lewis & Miall, 2006).

1.2.3 Perceiving versus acting in time

An additional distinction between perceiving and acting in time – at least in the subsecond range – has been also proposed. A relatively recent fMRI study that compared a closely matched time reproduction task (which is considered as a more motor temporal task) and time estimation task (which is more perceptual in nature) found evidence for both differential behavioural performance between the two tasks and differences in the activation patterns (Bueti, Walsh, Frith & Rees, 2008). The basal ganglia and cerebellum were found to be activated in both tasks whereas right pre-SMA, the left premotor cortex, the inferior parietal cortex and the visual extrastriate area V5/MT were activated more during the reproduction task.

Therefore, different studies suggest that there exist multiple temporal mechanisms, which may be flexibly engaged depending on the duration range and task requirements (Wiener, Matell & Coslett, 2011).

1.3 The Neural Basis of Timing

It seems that many brain structures both cortical and subcortical (basal ganglia, cerebellum, supplementary motor area, parietal and prefrontal activations) are involved in the representation of temporal information. The functional contribution of these areas though, as well as their interactions, is still not clear (Bueti & Macaluso, 2011).

1.3.1 The role of the cerebellum

The **cerebellum** seems to be mainly involved in the explicit timing of brief intervals, and is particularly associated with discrete-discontinuous movements. Patients with cerebellar damage perform with increased variability and decreased accuracy both in duration discrimination (perceptual task) and in temporal reproduction as well as rhythmic tapping (motor temporal tasks) in the subsecond range (Grondin, 2010). Also, there is some evidence that transcranial magnetic stimulation (TMS) applied to the medial cerebellum impairs timing of visual stimuli whereas TMS applied to the lateral cerebellum impairs auditory but not visual timing (Coull, Cheng & Meck, 2011). The role of cerebellum for supra-second durations is debatable as some studies have found evidence for its involvement in the supra-second range whereas in other studies no such involvement was apparent (Gooch, Wiener, Wencil & Coslett, 2010; Koch, Oliveri & Caltagirone, 2009).

1.3.2 The role of basal ganglia and supplementary motor area (SMA)

Neuroimaging studies as well as studies in patients with Parkinson's disease have identified the involvement of the **basal ganglia** and particularly the **caudate** and **putamen** in the encoding of temporal intervals (Rao, Mayer & Harrington, 2001). In these studies it seems that activation of the basal ganglia in temporal tasks is independent of the duration range, the sensory modality of the stimuli etc. Thus, it has been suggested that the basal ganglia as well as **SMA** form a striato-cortical network and play a context independent, central role in temporal processing (Coull, Cheng & Meck, 2011). However, a recent voxel-wise meta-analysis of neuroimaging studies in time perception, identified only the SMA (and not basal ganglia) and the

right inferior frontal gyrus as being active across different duration ranges and tasks. This suggests that these two regions constitute part of the core network underlying temporal processing (Wiener, Turkeltaub & Coslett, 2010).

1.3.3 The role of frontal and parietal areas

Apart from the above anatomical regions, specific areas of the **frontal and parietal cortex** (with a **right hemispheric bias**) have been associated with temporal processing.

Right hemisphere damage has been linked to impairments in timing (Harrington, Haaland & Knight, 1998). Particularly the dorsolateral prefrontal cortex (**DLPFC)**, which also plays a critical role in working memory processes, and the right prefrontal cortex have been suggested to be involved in timing (Koch, Oliveri, Carlesimo & Caltagirone, 2002). Neuroimaging studies suggest that right DLPFC activity is more common in cognitive controlled than automatic tasks (Koch, Oliveri & Calatgirone, 2009).

Neuroimaging, TMS, and neuropsychological studies have also indicated that the **right posterior parietal cortex (PPC)** plays a role in temporal processing (Battelli, Pascual-Leone & Cavanagh, 2007; Alexander, Cowey & Walsh, 2005; Mohl & Pfurtscheller, 1991). For instance, right brain damage (RBD) patients with hemineglect– who suffer prominent spatial and attentional deficits - were found to be impaired in temporal reproduction as well as discrimination of suprasecond and millisecond intervals, both in comparison to healthy controls and RBD patients without neglect (Calabria et al., 2011; Danckert et al., 2007; Basso, Nichelli, Frassinetti & di Pellegrino, 2006). These studies indicate that the parietal cortex

plays a critical role in the processing of temporal information together with spatial information. fMRI studies have also suggested that the parietal cortex is involved in the translation of the temporal information into action (Grondin, 2010).

1.3.4 The role of V5/MT

Finally, a recent repetitive transcranial magnetic stimulation (rTMS) study produced evidence for activation of the **V5/MT area** – a region of extrastriate visual cortex (secondary visual cortex) usually associated with visual motion processing – during duration perception. This activation was exclusive to visual duration discrimination tasks (as activation of V5/MT found only for duration discrimination of visual stimuli and not of auditory) (Bueti, Bahrami & Walsh, 2008).

Overall, it is becoming increasingly evident that multiple neural systems are involved in temporal processing. It seems that there is a broad neural network for temporal processing which involves the co-activation of several anatomically discrete areas. Different parts of this network can be co-activated depending on different factors such as the duration range, the sensory modality, the nature of the task and the cognitive set. In any case, when the contribution of an area that is active during a temporal task is investigated, it is critical to distinguish between the task components that reflect pure temporal processing and those which result from general cognitive components (such as attention, working memory, etc) and are shared by non temporal tasks.

1.4 The Main Models of Temporal Processing for the Subsecond Range

Several models have been developed to describe temporal processing in the millisecond range; there are two broad categories of models, **dedicated** (or extrinsic) and **intrinsic** (Spencer, Karmakar & Ivry, 2009).

1.4.1 Dedicated models of timing: scalar expectancy theory (SET)

Dedicated models of timing refer to specialized neural mechanisms for the representation of temporal information. Clock-counter models constitute a main subcategory of dedicated models and they have been extensively used in human and in animal cognition literature. According to these models, temporal judgements are based on an internal clock. This internal clock is composed of a pacemaker which emits regular pulses and an accumulator which keeps a count of emitted pulses. The pulse count provides a linear metric of time and explicit temporal representations (Karmakar & Buonomano, 2007).

Scalar Expectancy Theory (SET) has been the dominant theoretical model attempting to describe the behavioural mechanisms underlying time perception for the past 30 years. SET has was first developed by Gibbon (1977) and Gibbon, Church & Meck, (1984) and after further developed by Wearden (1991). The internal clock, according to SET, consists of an internal pacemaker, a switch and an accumulator (see Figure 1) (Penton-Voak, Edwards, Percival & Wearden, 1996). The pacemaker generates pulses, which are counted and stored by the accumulator via a switch which closes at the onset of a timed stimulus and opens at the offset of the

stimulus (Droit-Volet, Meck & Penney, 2007). The number of pulses counted by the accumulator during a specific time interval represents the subjective perceived duration of this interval (Ulrich, Nitshke & Rammsayer, 2006). The switch of the clock is supposed to oscillate between open and closed states and is usually associated with attention. When full attention is dedicated to temporal processing then the switch remains closed for longer time and more pulses are counted. When attention is driven away from timing then some pulses get lost resulting in underestimations of intervals. Latencies of the switch at both onset and offset of the timing of an interval can explain part of the variance that is observed in temporal tasks performance (Grondin, 2010).

Apart from the internal clock, SET involves two other stages, a memory stage and a decision stage. During these stages, the contents of the accumulator which are temporarily stored in short-term memory are compared to previously stored representations of temporal intervals in long-term memory (reference memory), and the duration judgment takes place (Wearden, 1999). This model attributes distortions in duration primarily to changes in the rate of internal information processing, which can be caused by various factors such as attention, arousal levels, emotions etc. An increase in this rate causes the pacemaker to produces more ticks and thus leads to duration dilations (Eagleman & Pariyadath, 2009).

Dedicated models of timing such as SET have the advantage that they are straightforward, widely applicable and have been quite successful in explaining behavioural/psychophysical data. Evidence in favour of this type of model comes from studies that show similar performance between motor and perceptual temporal processing and different sensory modalities (Wiener, Matell & Coslett, 2011). The

fact that humans are able to compare time across different modalities suggests some sort of central supramodal mechanism. A neural basis of a dedicated model of timing would require the identification of neural regions that would be specialized in different components of temporal processing. The cerebellum, for example, is a candidate for the representation of temporal intervals (Ivry & Schlerf, 2008).

However dedicated models of timing do not necessarily require timing mechanisms to be localized at a single brain region. Instead, temporal representations can result from activity across a network of neural regions with different components of timing being distributed across different areas. Recently, evidence coming from EEG, fMRI studies and single cell recordings has suggested that SMA is a plausible neural substrate of the accumulator component of the internal clock (Casini & Vidal, 2011). Despite the strength of these clock models in making testable behavioural predictions, their relevance to brain mechanisms is still unclear. In fact, internal clock-like mechanisms have found little support from electrophysiological and anatomical data. A few studies have shown evidence that at least under some circumstances temporal processing seems to be modality, duration and task specific and also mediated by local neural structures (Wiener, Matell & Coslett, 2011). The main weakness of clock models is that they fail to account for the dissociations observed in temporal processing (between different duration ranges, motor and perceptual timing etc) (Wittman & van Wassenhove, 2009).

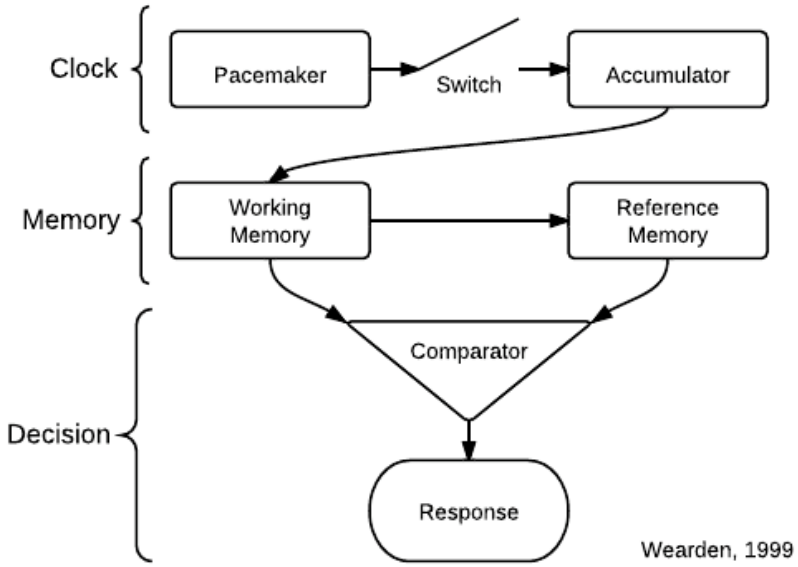


Figure 1. Schematic diagram of the SET model.

1.4.2 Intrinsic models of timing

Thus, a number of alternative models have been suggested for temporal processing. A quite different perspective is offered by the other main category of models, labelled: the intrinsic models of timing. Intrinsic models hold that temporal processing is an inherent property of neural circuits, and that the same circuits can process different types of sensory information such as spatial information, temporal information, motion etc. in a complex way (Buonomano, Bramen & Khodadadifar, 2009). Temporal processing according to these models does not depend on the recruitment of a specialized mechanism and can potentially occur separately in multiple loci. This suggests that timing is dependent on the properties of the local neural circuit, which can differ across modalities. Therefore, duration perception of visual stimuli would depend on the neuronal properties in visual regions whereas auditory duration perception would depend on the dynamics in auditory areas (Ivry

& Schlerf, 2008). This modality specific perspective is supported by recent studies, adopting "adaptation to flickering stimuli" paradigms, and showing that visual timing in the millisecond range seems to be spatially localized (Ayhan, Bruno, Nishida & Johnston, 2009). More specifically, adaptation to a drifting grating led to underestimations of subjective durations of subsequent stimuli that appeared at the same location but not of stimuli that appeared at different locations. The compression of duration of visual stimuli and not auditory that has been observed around saccadic eye movements offers further evidence for modality specific temporal mechanisms (Burr, Tozzi & Morrone, 2007).

A. State-dependent network (SDN)

State-dependent network (SDN) is an intrinsic model that has recently been developed and studied quite extensively. According to SDN timing is an inherent property of a neural network – which emerges from the complexity of the networks as well as the presence of time dependent neuronal properties – and it is represented as specific states of this network (Karmakar & Buonomano, 2007). Temporal processing does not rely on a linear metric of time such as clock ticks. When a series of intervals is presented, instead of measuring each one separately, temporal processing occurs continuously. As a result the series of intervals is represented as a temporal object (Karmakar, 2011). The network begins in a baseline state. The arrival of a stimulus changes this state by engaging a number of neuronal properties such as short-term synaptic plasticity. The response of the network to the arrival of subsequent sensory stimuli is dependent on the network's recent history such as the changes that the first stimulus induced at the network's state. Therefore in a task

where the durations of two sequential stimuli have to be compared (as with the duration discrimination paradigm) the presentation of the first stimulus influences the temporal processing of the second stimulus.

Temporal information can be measured independently in an SDN, but only in the case that the network has had enough time to reset and return to its baseline state. Some experiments that manipulated the duration of the interstimulus interval (ISI) revealed that the time it takes for the network to return to its initial state seems to be between 250 ms and 500 ms at least for auditory stimuli (Buonomano, Bramen & Khodadadifar, 2009). A problem with the SDN however is that the processes underlying SDNs function over a limited duration range (few hundreds of millisecond), which can be restrictive in the generality of the predictions of this model. Moreover, in SDN temporal representations are highly context dependent (on task, modality, duration etc), which suggests that the output of the network might be highly susceptible to noise. This sensitivity to noise would lead to much variance in the performance of temporal tasks and could not explain the fact that the temporal performance is actually quite precise. However, recent simulations have shown that SDNs can tolerate some levels of noise (Buonomano & Maas, 2009).

B. Eagleman's model

Another intrinsic model of timing that adopts a different approach is Eagleman's model (2008). Similarly to the SDN model, Eagleman's model depends on generic features of neural activity and is modality specific. Within this framework, it is suggested that the subjective duration of a stimulus reflects the magnitude of the neural response to the stimulus. Therefore, factors that cause an increase in

amplitude of neural responses also cause duration dilations. For example, when a series of identical stimuli are presented and then a novel stimulus appears, participants are likely to report the duration of the novel stimulus as longer even if the physical duration of the stimulus is not different from the repeated stimuli. Eagleman's model attributes this effect to repetition suppression; repeated presentations of a stimulus in higher cortical areas leads to decreased amplitude of the neural response, which has been suggested to result in reduced perceived duration of stimuli. This suppression recovers with time, a feature analogous to the reset period in SDN.

Eagleman's model seems to be quite successful in explaining a variety of duration distortions (Eagleman & Pariyadath, 2009). For instance, the underestimation of duration that is observed during saccades is attributed to the reduced visibility of visual stimuli around the saccadic target, which leads to a smaller magnitude neural response and therefore duration compression. Also, this model is supported by studies that have shown that higher magnitude stimuli (for example stimuli of larger quantity or larger size etc.) appear to have longer duration than equal or smaller magnitude stimuli. This relates to the Tau and Kappa effects according to which the duration and the spatial length of stimuli affect each other; stimuli of longer duration are perceived to have also larger spatial distance. Similarly a spatially larger stimulus seems to have longer duration. Despite the advantages of this model for explaining various distortions of perceived duration, it does not clearly account for attentional effects. Many of the above effects could actually be explained as effects of attention rather than neural amplitude.

1.4.3 Evaluation of intrinsic models

Although intrinsic models of time offer a different perspective about the mechanisms underlying temporal processing and seem to overcome some of the problems of dedicated models such as accounting for local effects, modality, task, duration differences, they still confront some limitations. Generalization of perceptual learning on other sensory modalities and/or duration ranges is an example. If temporal processing occurs in local networks and thus it is modality specific, it is unclear how training on an auditory temporal task would improve the performance in a visual temporal task (Warm, Stutz & Vassolo, 1975). However, evidence for crossmodal transfer is contradictory, as recent studies have not found transfer of perceptual temporal learning from the auditory to the visual modality (Lapid, Ulrich & rammsayer, 2009).

Furthermore, comparisons of durations of stimuli belonging to different sensory modalities, frequencies etc are possible, which suggests that there is some level of similar mapping between different local networks. Buonomano, Bramen & Khodadadifar (2009) have proposed that different sensory representations – as a result of experience – may rely on a common higher order representation. Therefore, it maybe the case that there are both local, task and modality specific networks responsible for temporal processing as well as more generic representation mechanisms which allow the comparison between different channels. That can be supported by neuroimaging evidence as was described in the previous part, with the existence of areas that seem to be activated across all temporal tasks and areas that are task, modality, and duration specific. Finally, it is quite important, for all kinds of

models, to distinguish between pure temporal effects and non-temporal factors that can affect temporal performance (Spencer, Karmarkar & Ivry, 2009). These factors can be independent of the mechanisms underlying temporal processing and as such are critical for both intrinsic and dedicated models of timing.

1.5 Paradigms Used in Time Perception Research

1.5.1 Prospective versus Retrospective paradigms

In temporal perception studies there is an important methodological distinction between **prospective** and **retrospective** paradigms. In the case of the prospective paradigms, participants know in advance that they are going to perform a task in which a duration estimation or judgment is going to be needed. In contrast, when participants have to perform a retrospective task, they are not warned in advance, but they are unexpectedly asked to give duration judgments after the presentation of the temporal interval. Differences in the performance of participants between prospective and retrospective paradigms have been observed with duration judgments, with the prospective paradigms being more accurate and less variable (Brown, 1985). In the present work only prospective temporal paradigms have been employed and thus some specific examples of extensively used prospective tasks are being presented.

1.5.2 Prospective tasks: Motor versus Perceptual

There are two main types of prospective temporal tasks: motor tasks where the motor response is itself timed, and perceptual tasks where the user chooses a

response to indicate their judgment of stimuli durations. (Macar, Lejeune, Bonnet, Ferrara, Pouthas, Vidal & Maquet, 2002).

A. Motor tasks

Temporal production and **temporal reproduction** are considered motor temporal tasks. During the **production** task participants are asked to produce an interval of a specific duration (e.g. 500 ms or 1 sec etc.), by pressing a key twice, to indicate the beginning and end of the duration. **Temporal reproduction** involves two stages: during the initial encoding stage participants are being presented with a stimulus – visual, auditory etc – for a specific duration and then asked to estimate its duration. Then, during the reproduction stage participants are required to reproduce the previously presented duration by pressing and holding a key.

B. Perceptual tasks

Verbal estimation, **duration bisection**, **duration generalization** and duration **discrimination** are considered as more perceptual tasks and are commonly used in the time perception literature. During **verbal estimation**, participants are simply presented with stimuli of different durations and they are asked to give verbal estimates of the presented duration. Duration bisection involves two stages: during the first phase of the temporal bisection task, participants are presented several times with two standard intervals, a short and a long one. In the second phase they are presented with a range of comparison durations and their task is to classify these stimuli as more similar to the long or the short standard (short – long judgments) (Droit-Volet, Tourret & Wearden, 2004). The **bisection** method has been used

particularly within the framework of SET in order to test its predictions. The **temporal generalization** task involves the sequential presentation of two stimuli. Participants are required to judge whether or not the two stimuli were equal in duration (Wearden, 2008).

The **duration discrimination** task is widely used in the research of brief durations' processing and is useful for the measurement of participants' psychophysical performance. In the present work the duration discrimination paradigm was used in most of the experiments, specifically the **reminder version** of duration discrimination (Lapid, Ulrich & Rammsayer, 2008).

In the reminder version each trial consists of a standard stimulus followed by a comparison stimulus. The standard stimulus is the same across trials, whereas in each trial the comparison duration is randomly chosen from a set of durations which can be shorter or longer in duration than the standard. Participants are asked to judge whether the second stimulus (the comparison) was longer or shorter than the standard.

Plotting the proportion of a participant's "longer" responses against the comparison stimuli durations produces a psychometric sigmoid function. Also, the **difference limen (DL)** and **Weber ratio (WR)** are calculated, based on this psychometric function. These two values are measures of the temporal sensitivity of participants. DL is an index of absolute temporal sensitivity and it measures the smallest duration difference that can be reliably discriminated amongst the durations in the set of stimuli used, a kind of "just noticeable difference" (Droit-Volet & Wearden, 2002). WR is a measure of a relative temporal sensitivity (it is calculated by DL divided by a measure of duration range). It provides a measure of temporal

variability that takes into account the duration being timed. In both measures, lower values indicate higher temporal sensitivity and thus better performance. Apart from these measures of participants' precision of temporal judgments, the **bisection point (BP)** is also calculated, which is defined as the stimulus duration giving rise to 50% "longer" responses. It can be conceived of as the point of subjective equality in duration discrimination, the duration at which a participant is equally likely to classify the duration as "shorter" or "longer"; it is also a measure of the direction of the bias (overestimation or underestimation).

1.6 Effect of Non-Temporal Factors on Duration Judgments

The subjective duration of a stimulus can be influenced by several non temporal factors in addition to its objective length, for example, physical characteristics of the stimuli (e.g. type of intervals, filled versus empty, brightness etc) or the state of participants (e.g. levels of arousal, attention, body temperature etc) (Wearden, Todd & Jones, 2006; Burle & Casini, 2001).

1.6.1 The effect of stimuli features

Discrimination of **filled** intervals seems to be more precise than discrimination of **empty** intervals (Rammsayer & Lima, 1991). In empty intervals, only the onset and the offset of the stimulus are marked by a brief sensory signal such as a click or a brief light). In contrast, in filled intervals a signal is presented continuously throughout the interval. However, the superiority of filled intervals in duration perception has been disputed by other studies that had reported the opposite effect –

superiority of empty intervals – or failed to reveal differences between these two types (Grondin, 1993). These discrepancies in the findings of different studies between the performance of filled and empty durations are suggested to depend on the duration range, the type of the discrimination task and the modality and duration of the marker signal (Rammsayer & Leutner, 1996). For example, a recent study established higher discrimination performance for filled auditory intervals specific to the 50 ms duration range (Rammsayer, 2010).

1.6.2 The effect of participants' state

Manipulations of participants' body temperature have also been shown to affect duration perception (Wearden, Todd & Jones, 2006). Most of these studies are quite old (some more than 80 years old). In general, raising the body temperature – using fevers occurring naturally as the result of an illness, heated rooms, suits, or helmets, and diathermy (which is the passage of high-frequency electric current through the body – resulted in duration overestimations. In contrast lowering the body temperature – through cold water immersion (through diving or in laboratory settings) and exposure to a cold room – has been found to cause underestimation of durations. The results of these studies has been mainly attributed to changes in the internal clock speed induced by changes in body temperature with the internal clock speeding up when temperature increases and slowing down when temperature decreases.

Another aspect of the state of participants that can affect perceived duration is the arousal level. Increase of arousal by administering amphetamine has been shown to result in overestimation of intervals. Administration of antipsychotics

(haloperidol) decreases arousal and produces underestimations (as if the internal clock was running slower) (Burle & Casini, 2001; Mella, Conty & Poutha, 2011).

In the present thesis, the effects of three non-temporal factors – modality (visual versus auditory), spatial location and attention – on subsecond duration judgments were mainly examined. The literature relevant to these factors is going to be presented and discussed in detail in Chapter 2.

1.7 Summary

This Chapter set out to describe briefly the history of time perception research in cognition and present the separate systems underlying temporal processing. It provided the general background by identifying and discussing the contribution of the main anatomical structures related to timing as well as reviewing the main models of temporal processing. It also presented some commonly used paradigms in temporal research and gave more details about the task adopted in the present work. The last section gave some examples of how extra temporal factors can distort subjective duration and introduced the three main subjects of interest of the present research that are going to be the topic of the following chapter.

Chapter 2 –

INTRODUCTION II:

INFLUENCE OF MODALITY, SPATIAL LOCATION AND ATTENTION

As mentioned at the end of Chapter 1, the perceived duration of events might differ according to many extra-temporal factors including physical characteristics of the stimuli and the inner state of participants. In this chapter the main variable of interest to the present thesis – namely the effects of signals' sensory modality, spatial location and participants' attention – shall be explored.

2.1 Visual – Auditory Differences in Timing

There is evidence that the sensory modality of the stimuli (visual versus auditory) is one of the main factors affecting the subjective duration of stimuli. The differences between modalities are quite consistent and have been replicated by different experimental procedures and in different duration ranges. Specifically, stimulus modality seems to play a major role in both perceived duration and in accuracy of temporal judgements (Droit-Volet & Wearden, 2002).

2.1.1 The effect of modality on temporal precision

It has been suggested that audition often dominates the visual modality for temporal processing in contrast to the spatial processing where vision is the dominant modality (Guttman, Gilroy, & Blake, 2005). Auditory temporal judgements are usually found

to be more accurate than visual temporal judgements. Higher temporal sensitivity for auditory stimuli has been observed in a wide range of paradigms. For example, participants have been found to have both higher accuracy and faster reaction times (RTs) for auditory stimuli than for visual in a temporal generalization task (N' Diaye, Ragot, Garnero & Pouthas, 2004). In paced finger tapping, less variability is observed for auditory than for visual signals (Jancke, Loose, Lutz, Specht & Shah, 2000). In temporal order judgment tasks, also, participants are found to perform better in the auditory modality, especially when the interstimulus interval is short (Kanabus, Szelag, Rojek & Poppel, 2002). Furthermore, according to the results of audiovisual temporal alignment studies, an auditory signal needs to be delayed by around 40 to 50 ms in order to be perceived as temporally aligned with a visual stimulus (Burr & Alais, 2006). Parkinson's disease patients and children with ADHD have also been found to exhibit better temporal acuity in the auditory modality than visual, which demonstrates the robustness of the effect (Plummer & Humphrey, 2008; Smith, Harper, Gittings & Abernethy, 2007).

Intrinsic perceptual features of visual and auditory stimuli have been suggested to contribute to these effects, particularly, the fact that visual stimuli are processed more slowly than auditory. Auditory stimuli take up to 10 ms to reach higher processing areas while visual stimuli require around 50 ms. Moreover, it has been proposed that auditory temporal information is processed relatively automatically in contrast to the visual temporal information processing which requires controlled attention. A recent ERP study provided some evidence for the automatic processing of auditory temporal information, by showing that the mismatch negativity (MMN) component – which is used as an index for

investigating automaticity of auditory processing – was not modulated by attention whereas the visual mismatch negativity (vMMN) – the homolog of the auditory MMN – was modulated by attention (Chen, Huang, Luo, Peng & Liu, 2010).

However, other recent studies have challenged this view of the absolute dominance of the auditory modality in the temporal processing. For example, a study examining modality and intermittency effects on duration judgments found higher temporal sensitivity in the auditory domain only in the case of steady stimuli. The temporal resolution of visual flickering stimuli was similar to all auditory stimuli (Ortega, Lopez & Church, 2009). Furthermore, conflicting visual information was found to robustly shorten or lengthen the subjective duration of auditory signals whereas auditory distractors managed to alter the subjective duration of visual stimuli in very few cases (Van Wassenhove, Buonomano, Shimojo & Shams, 2008).

2.1.2 Modality effect on perceived duration

Auditory stimuli are often perceived to have different durations than visual stimuli even when the actual physical length of the stimuli is exactly the same. A common result from studies using a range of temporal tasks (temporal bisection, duration discrimination, temporal generalization, production, verbal estimation etc) as well as a variety of different stimuli durations is that “sounds are judged as longer than lights”. Thus, visual stimuli are often experienced as shorter than equivalent duration auditory stimuli (Wearden, Edwards, Fakhri &Percival, 1998).

In particular, several studies using the temporal bisection paradigm have observed differences in the psychophysical functions between auditory and visual trials, with the auditory psychophysical functions being displaced toward the left

(which shows greater overestimation of the auditory stimuli than of the visual ones) (Droit-Volet, Tourret & Wearden, 2004). So, when participants have to classify a range of stimuli as more similar to the previously presented short or long standard, they exhibit a higher proportion of LONG responses in the auditory than in the visual trials.

A. Factors underlying the visual – auditory differences in perceived duration

Several potential factors have been proposed to explain this modality effect. The most prominent explanation states that the effect is due either to differences in the speed of an internal clock (i.e. it runs faster with auditory stimuli than with visual stimuli) or differences in the variance of the latency of the switch that connects the pacemaker to the accumulator. According to this internal clock model, if the modality affects the speed of the clock and the internal clock runs faster with auditory stimuli than with visual ones, that means that more pulses are counted during the processing of auditory stimuli and therefore the auditory temporal intervals are overestimated in comparison to the visual ones. Alternatively, if modality affects the variance of switch latencies, the switch is less variable with auditory stimuli and closes earlier than with visual stimuli, again allowing more pulses to be counted with auditory stimuli (Droit-Volet, Meck & Penney, 2007).

These two hypothetical mechanisms underlying the modality effect can be distinguished in behavioural experiments, as the faster clock explanation would predict a multiplicative effect of the sensory modality of stimulus across a range of stimulus durations (Droit-Volet et al, 2007). Thus, the differences between the

auditory and visual stimuli would be larger for longer than for shorter times. In contrast, in the case of the differences in switch latency hypothesis an additive effect of stimulus modality across a range of durations is predicted. This means that the effect is independent of the duration values used. Behavioural results (usually using the temporal bisection procedure) have offered stronger support for the clock speed hypothesis by showing proportional differences between auditory and visual duration judgments.

B. Mechanisms giving rise to clock speed differences between modalities

Two mechanisms underlying the difference in clock speed between modalities have been suggested. According to the first one the difference in the clock speed is actually due to differences in the speed of the pacemaker for the different modalities. Thus, the pacemaker produces pulses more quickly with auditory stimuli than with visual stimuli. An alternative interpretation has been provided by Penney, Gibbon & Meck (2000) and suggests that the differences between clock speed in auditory and visual stimuli are caused by oscillations of the switch between opened and closed states duration measurement, which results in some pulses being missed by the accumulator. It is supposed that, due to attentional capture differences, the switch is more easily maintained in the closed state when attending to the duration of auditory stimuli, so fewer pulses are lost. According to Penney et al. (2000), there is greater attentional allocation to auditory stimuli relative to visual stimuli. Greater attentional allocation can affect temporal judgments by helping to reduce the variance of switch latencies, thus better maintaining the switch in a closed state.

C. When do modality differences in perceived duration appear?

The modality effect (auditory intervals judged as longer than visual ones) has been found to occur under specific conditions. Within the temporal bisection task, the effect occurs only when both auditory and visual stimuli are presented within the same session (Penney, Gibbon & Meck, 2000). This was explained in terms of a "memory mixing" mechanism, by which a common reference stimulus (combination of the visual and auditory standard stimuli) is formed and stored in memory. Participants compare the following visual or auditory stimuli to this "common" standard – which was suggested to be dominated by the auditory stimuli – and this leads to longer judgments of the auditory stimuli. Therefore, the longer judgments of auditory stimuli were explained by a combination of differences in the speed of the clock between modalities and the memory mixing across the two sensory modalities. However, Wearden, Todd & Jones (2006), using a variety of experimental paradigms, observed a similar effect without combining auditory and visual stimuli in a single session, which could not be explained in terms of "memory mixing". Consequently, it is still unclear when and why these modality differences occur.

D. The role of memory representations in the modality effect

Ogden, Wearden & Jones (2010), set out to explore the role of the memory representations of visual and auditory stimuli in the effect of modality on duration perception. Their findings contradicted the hypothesis that representations of auditory durations are more dominant in memory. The study used a modified temporal generalization paradigm in order to examine the effects of interference

between different standard durations stored in the reference memory. In this task, participants were presented with an initial standard stimulus (A) and they then had to compare its duration with a range of comparison durations. After, participants were presented with a different duration standard (B) and another range of comparison durations. Finally, after a delay period of variable length, participants were presented with the comparison durations of the standard A – but without any further exposure to either standard – and were required to give the duration judgments based on their memory of the standard duration (A). The two standards differed in duration and they could be either auditory, visual or crossmodal.

The results of the above study showed different patterns of performance between the ways that visual and auditory intervals are encoded and stored in reference memory: when multiple auditory standards needed to be encoded and stored, there was a systematic interference between them suggesting that reference memory has a limited capacity for auditory stimuli. In contrast, there was no systematic interference in the case of multiple visual standards, a finding that indicates that the reference memory has the capacity of accurately storing the durations of multiple visual signals. Moreover, no evidence for interference was found in the crossmodal conditions. Therefore, the results of this study indicate an advantage for visual encoding for multiple temporal stimuli, which seems surprising in the light of the theory for auditory dominance in temporal processing. This seems to contradict previous studies that have demonstrated more variable memory representations for visual stimuli at least for young children (Droit-Volet, Tourret & Wearden, 2004). Ogden et al. (2010) suggest that greater variability in visual

temporal judgments does not result from more variable representations of visual intervals but rather from more variable perceptual processes.

In the present thesis visual and auditory temporal judgments were compared using the duration discrimination paradigm. One of the aims was to further explore the modality effect on temporal judgments using either blocked or mixed modality design. In the experiments where the blocked modality design was used participants were presented with a block of visual trials followed by a block of auditory trials. With this configuration, the modality effect on the perceived duration is not usually observed. In the experiments where the mixed design was used, visual and auditory trials were presented randomly intermixed within the same session. In these experiments, we expected to replicate the previously reported difference between visual and auditory temporal judgments, with a higher proportion of LONGER responses in the auditory trials. Moreover, the present experiments differed in attentional demands (by varying the number of location conditions which shall be described in detail in the following section). An additional aim of the present thesis was to investigate how the difference in processing loads between the tasks would affect visual and auditory temporal judgments.

2.1.3 Supramodal vs modality specific clock models

As mentioned in Chapter 1, an unanswered question in temporal perception literature is whether there is a central supramodal temporal mechanism, or rather distinct timing mechanisms for each modality. Unequal effects of extra-temporal factors on visual and auditory duration judgments could provide evidence for separate

underlying mechanisms. In contrast, if the effect of the non-temporal factors is similar across modalities, then that could provide further evidence for a central timing mechanism. Previous findings have been inconsistent on this matter. For example, stimulus expectancy had been found to affect the perceived duration of both visual and auditory stimuli by expanding the duration of unpredicted stimuli. Also, perceptual learning in temporal discrimination on the tactile modality has been found to generalize to the auditory domain (Nagarajan, Blake, Wright, Byl & Merzenich, 1998). These findings could support the notion of a supramodal timing mechanism unaffected by the specific modality features.

Nevertheless, a more recent study, also using a perceptual learning paradigm in time discrimination, found evidence that contrasts the view of a single common timing mechanism for different modalities. Specifically, training in auditory temporal discrimination did not facilitate participants' performance in visual discrimination of the same time intervals (Lapid & Ulrich, & Rammsayer, 2009). Thus, there was no cross-modal transfer from the auditory to visual modality, as it would be expected given a single amodal temporal mechanism.

Therefore, if non temporal factors such as the diverse attentional demands of the current experiments differentially affect visual and auditory duration judgments, then this could be taken as evidence supporting the function of modality specific timing mechanisms.

Most of the previous experiments assessing the effect of modality on temporal judgments have not manipulated the location of the stimuli. Thus, visual stimuli were mainly presented on the centre of the screen and auditory stimuli were

presented binaurally. An additional aim of the present work was to investigate the effects of spatial location on duration discrimination.

2.2 The Effect of Space on Temporal Processing

The relationship between time and space has been a fundamental issue in physics. Moreover, temporal and spatial aspects are intertwined in the performance of various everyday activities. In fact, temporal mechanisms are crucial for making predictions or taking actions in space (Bueti, Bahrami & Walsh, 2008). Converging evidence from different areas of research – such as the effect of saccades, of local visual adaptation, of spatial location etc – points out to a close relationship between spatial and temporal processing in cognition. However, the exact nature of the cognitive mechanisms underlying the relationship between these two aspects as well as the common brain areas, are still unclear.

2.2.1 Spatial – temporal interactions in language

In several languages such as English, people use spatial metaphors when they talk about time (e.g. long meeting, short concert etc.). This relationship between space and time in language seems to be asymmetrical, as people do not use temporal metaphors in order to talk about space (Casasanto & Boroditsky, 2008). This pattern in the use of metaphors in language was found to extend beyond the domain of language. In a series of psychophysical experiments participants were presented with a line, which increased in length over time (Casasanto & Boroditsky, 2008). Their task was to reproduce either the duration or the spatial displacement of the line. The

duration judgments were dependent on the spatial information but the reverse was not true.

2.2.2 Tau and Kappa effects

The demonstration of Tau and Kappa effects in psychophysical studies has been used as evidence for the close relationship between spatial and temporal dimensions. In these experiments participants were presented with two intervals marked by three light bulbs arranged in a row which flashed one after the other. The spatial and temporal interval between these stimuli was variable. The participants' task was to compare either the spatial or temporal extent of the two intervals. The Tau effect refers to the influence of temporal information over spatial judgments; participants were actually found to judge intervals of greater temporal separation as more spatially separated. Kappa effect refers to the influence of spatial information in duration judgments with participants duration judgments found to increase as a function of the spatial distance between stimuli (Correa & Nobre, 2008). However, the interpretation of these effects in terms of influence of spatial and temporal components of the stimuli has been criticized by subsequent research. These effects were alternatively attributed to implicit judgments of imputed velocity (Oliveri, Koch & Caltagirone, 2009).

The effect of spatial distance on duration judgments has also been investigated in the auditory modality. Participants were presented with three intervals marked by four auditory signals. The signals were either delivered via earphones binaurally or via four loudspeakers that were aligned horizontally from left to right. Participants had to judge if the last interval was presented for a longer or shorter

duration than the previous intervals. The Kappa effect in the auditory modality was observed under some experimental conditions; perceived duration increased as a function of spatial distance between two marker sources when more than two loudspeakers were used to mark the series of intervals (Grondin & Plourde, 2007).

2.2.3 The effect of motion adaptation on perceived duration

The perceived duration of visual stimuli can be affected by adaptation to drifting motion or visual flicker (Ayhan, Bruno, Nishida & Johnston, 2011). After adapting to a fast moving grating (20 Hz) – or flicker– appearing to one side of fixation (left or right), two sub-second visual stimuli (drifting gratings or drifting visual stimulus) were sequentially presented to the adapted and non-adapted regions of the visual field. The participants' task was to report which interval lasted longer. The stimuli that were presented on the adapted region of the retina (10 Hz) appeared shorter than those displayed on the opposite, non-adapted location (Johnston, Arnold & Nishida, 2006). This compression of duration as an effect of adaptation also occurred when the stimuli were presented at different locations in the same hemifield (the stimuli were located on the top and bottom of fixation within the same hemifield). Furthermore, there is some evidence for the opposite effect (expansion instead of compression of apparent duration) for positions that are located at some distance from the adaptor.

Perceived duration has previously been found to depend to some extent on the stimulus (flicker) frequency. The duration of a stimulus is underestimated when compared to a previously presented higher frequency stimulus, whereas it is overestimated when compared to a lower frequency stimulus. Thus, the duration

effect that was described in the previous paragraph could be attributed to an effect of stimulus frequency. However, this account seems to be unlikely as compression of a 10 Hz stimulus occurred not only after adaption to 20 Hz but also after 5 Hz – although in smaller extent (Bruno, Ayhan & Johnston, 2010).

The reduction of subjective duration after such adaptation is inconsistent with central clock accounts, as it implies the existence of spatially localised components for visual duration perception (Johnston, 2010). The neural locus of this effect has been suggested to be pre-cortical as the compression of duration occurs independently of the relative orientation of the stimuli that are used and it can also take place even in the case of invisible (60Hz) flicker (Ayhan, Bruno, Nishida & Johnston, 2009). The magnocellular system has been proposed as a plausible candidate.

A. Spatiotopic vs Retinotopic adaptation-based compression of subjective duration

The neural locus of the adaptation-based compression of duration has been the centre of an interesting debate: is the effect of adaptation retinotopic or spatiotopic? A retinotopic effect of adaptation – specific to the part of the retina that was adapted – would suggest an early locus of visual processing (magnocellular pathway) where receptive fields are mapped to the retina. In contrast, a spatiotopic effect of adaptation – when the stimulus is placed in the same screen position as the adaptor (specific to the region of the external space) – would indicate the involvement of higher levels of processing such as the lateral intraparietal area (LIP) which has

receptive fields strongly affected by eye movements in order to give it a transient spatiotopicity (Burr & Morrone, 2006).

In order to test the spatiotopic and retinotopic effects of adaptation, participants were presented with test stimuli in three possible locations: a) at the same position the adaptor was appearing on the screen (spatiotopic), b) at the same position the adaptor occupied relative to fixation (retinotopic), or c) a totally different position (control condition) (Morrone & Burr, 2010). The duration of these stimuli was compared to the duration of another stimulus (probe) presented in a non-adapted region.

Two different components of adaptation appeared depending on the apparent speed of the adapted and non-adapted regions; when the apparent speed of the stimuli appearing in the adapted and non adapted regions were not matched, both retinotopic and spatiotopic adaptations took place. However, when the apparent speed of the probe and test stimuli were matched, the retinotopic effect disappeared and only spatiotopic adaptation was observed (Burr, Cicchini, Arrighi & Morrone, 2011). Hence, it was suggested that adaptation occurs at both lower and higher levels of processing. In contrast to these studies, Johnston, Bruno & Ayhan (2011) argue that they have found more robust evidence for the existence of retinotopic adaptation in comparison to spatiotopic adaptation, which in their studies was found only when the test stimulus (in the adapted region) was presented first.

2.2.4 Saccadic effects on duration judgments

The effect of saccades on timing has been the basis of many arguments supporting the tight connection between spatial and temporal processing. Saccades are ballistic eye movements and are used in order to redirect the fovea to the object of interest by

shifting the gaze to a new location in the visual field (Morrone, Ross & Burr, 2005). Several studies have provided evidence for two distinct effects of saccades on the perceived duration of events, chronostasis and saccadic temporal compression.

A. "Chronostasis" or the "stopped clock" illusion

Saccadic chronostasis refers to the overestimation of the duration of a visual stimulus that immediately follows a saccade. It is also called the "stopped clock" illusion because it is common to observe when looking at a clock (Yarrow, Haggard, Heal, Brown & Rothwell, 2001). The clock hand seems to appear to stay longer at the first position that is seen than at the following ones (Yarrow, Haggard & Rothwell, 2004). Chronostasis illusion is thought to be the result of a compensation mechanism of the brain for the time lost during the saccades. Furthermore, it seems that it does not depend on spatial attention shifts that accompany saccades (Yarrow, 2010).

Different mechanisms underlying chronostasis have been suggested; the shift of the perceptual onset hypothesis and the arousal hypothesis are the two main accounts. The arousal hypothesis suggests that making a saccade potentially increases physiological arousal. This account predicts a proportional variation in the size of the dilation. According to the shifted perceptual onset account, duration dilation occurs as a result of a tendency to make errors in the timing of the onset of the post-saccadic stimulus – because of the perceptual uncertainty which is caused by the saccadic suppression – and antedating it pre-saccadically (Yarrow, Haggard & Rothwell, 2004). In contrast to the arousal hypothesis, the shifted perceptual onset account predicts a constant effect. Experimental evidence has mainly supported the shifted perceptual onset account.

Although chronostasis was initially thought to be tightly linked to the effect of saccades, subsequent research has shown that saccadic eye movements are not necessary for this phenomenon to appear. In fact, it can also occur with different types of voluntary actions such as key presses and voice commands, voluntary arm movements as well as with auditory stimuli (Georg & Lappe, 2007). For example, auditory chronostasis has been observed in auditory duration discrimination using monaural presentation of signals. Chronostasis in this experiment was observed when the duration discrimination was preceded by another task (pitch discrimination) on the opposite ear (Hodinott-Hill, Thilo, Cowey & Walsh, 2002). A more generic even-shift account of these chronostasis effects has been suggested according to which the perceived timing of any voluntary action shifts toward the time of the action (Park, Schalg-Rey & Schlag, 2003).

Chronostasis has also been attributed to spatial attention shifts, which accompany saccades. It could be the case that the implicit attentional resources that are recruited around saccade onset are responsible for the time dilation, as attention usually leads to time overestimations. Nevertheless, results from recent studies have suggested a certain degree of independence between attention shifts and saccadic chronostasis (Yarrow, 2010).

B. Saccadic temporal compression

Apart from the chronostasis effect several studies have shown evidence for a compression of perceived duration of visual events caused by saccadic eye movements (Morrone, Ross & Burr, 2005). This effect results from studies using a visual duration discrimination task. Participants were presented with two empty

durations each indicated by the brief presentation of two bars at the top and bottom of the screen. Their task was to compare the duration of the probe interval to the duration of the test interval while making large horizontal saccades. The participants underestimated the duration of the interval that was presented near the saccadic onset to about half the physical duration (Morrone & Burr, 2010). The duration compression has been considered an effect of the damping of attention during saccades. However, experimental results have shown that the attentional factors cannot fully account for the saccadic compression of time, as the saccadic effect is larger than the attention effect (Oliveri, Koch & Caltagirone, 2009).

This temporal compression seems to be tightly linked to the widely reported compression of space occurring during saccades, as both effects take place within approximately the same time period from shortly before to shortly after saccades and they both reach their maximum just at the start of the saccades. This similarity between temporal and spatial distortions during saccades suggests that both effects may be mediated by a common mechanism. A plausible interpretation for these compression effects is that saccades exert an influence on the temporal encoding of neurons of lateral intraparietal cortex (LIP) area. The results of a recent study also suggest that this saccadic compression extends also to numerosity with participants consistently underestimating random arrays of visual stimuli when they were flashed just before the saccadic onset (Binda, Morrone, Ross & Burr, 2011).

C. Saccadic duration compression versus Chronostasis

In contrast to chronostasis, the temporal compression is specific to visual stimuli as it is not observed with auditory clicks (Morrone & Burr, 2010). Hence, it seems that

the co-occurrence of temporal and spatial distortions occurs only in the visual domain suggesting distinct temporal mechanisms for the different modalities. In the case of the visual modality these temporal mechanisms are intrinsically connected to spatial processing.

Compression of duration around saccades is accompanied by an increase of precision in temporal judgements, which is not observed during chronostasis. Furthermore, chronostasis depends on the size of the saccade and the duration of the stimulus but it is not tightly linked to the time course of the saccade whereas temporal compression follows a specific time course, reaching its maximum at the beginning of saccades but at the same time it is independent of the saccadic size (Georg & Lappe, 2007). In fact, saccadic compression seems to have a constant size of about 50 -75 ms. Finally, chronostasis seems to be a local effect as the duration dilation does not extend to locations further away from the saccadic target, whereas the duration compression caused by saccades appears to be a more global phenomenon.

2.2.5 Representation of time through a left-to-right oriented line

Recent behavioural studies in the visual modality suggest an association of the right side of space with longer durations (or overestimation) and of the left side of space with shorter durations (or underestimation) (Oliveri, Koch & Caltagirone, 2009). Thus, a spatial representation of time, similar to what is used for numbers has been suggested.

A. Spatial-temporal association of response codes (STARC)

Valessi, Binns & Shallice (2008), demonstrated the presence of a compatibility effect between spatial and temporal magnitudes; participants had shorter reaction times if they were responding to relatively short durations with a left key and to relatively long durations with a right key. This effect was called the STARC effect (Spatial/Temporal Association of Response Codes) so as to resemble the conceptually related SNARC effect (Spatial/Numerical Association of Response Codes). The SNARC effect has been interpreted as an indicator of automatic access to number magnitude with a spatial representation of numbers as a point in a mental line oriented from left to right (Mapelli, Rusconi & Umilta, 2003). When participants are asked to perform a parity judgment task on Arabic numerals, their reaction times are faster when smaller numbers are responded to with a left key and when larger numbers are responded to with a right key. However, there is a difference between the SNARC and the STARC effects; whereas the SNARC effect occurs even when magnitude is not relevant to the task, the STARC effect has only been observed when duration is relevant to the task.

Therefore, temporal information was suggested to be represented visuospatially and to be part of a generalized magnitude system, together with other types of magnitude such as numbers (Cordes, Williams & Meck, 2007; Walsh, 2003). Evidence for this common magnitude system also comes from studies that compare participants' discrimination performance between different types of quantities. For example, Droit-Volet, Clement and Fayol (2008) compared the quantity discrimination performance of children and adults with three different types

of quantities: numerical, spatial and temporal. When discrimination trials were presented sequentially, all participants performed similarly between each type of quantity, although children exhibited lower sensitivity overall.

B. Left and Right sides of space & duration discrimination

Two recent studies reported overestimation or underestimation of duration with left or right side presentation or alternatively left or right side direction of spatial attention.

In the first study participants' spatial attention was manipulated using optokinetic stimulation in the form of drifting white lines (Vicario, Caltagirone & Oliveri, 2007). Optokinetic stimulation has been found to transiently move the attention towards a specific side of space. In this study, immediately following rightward or leftward optokinetic stimulation, participants had to perform a duration discrimination task in the visual modality. The results showed that moving the attention towards the right via rightward optokinetic stimulation led to overestimations whereas using leftward optokinetic stimulation induced a trend for underestimation, suggesting that time is represented linearly by means of spatial coordinates and spatial attention plays a role in the construction of this representation.

A subsequent study provided further evidence supporting the hypothesis of a mental linear representation of durations (Vicario, Pecoraro, Turriziani, Koch, Caltagirone & Oliveri, 2008). In this study, participants had to perform a visual duration discrimination task. They were presented with two visual stimuli (numbers or circles) a standard, followed by a comparison. The duration of the standard

stimulus was fixed at 300 ms whereas the duration of the comparison varied randomly per trial, ranging from 150 to 450 ms in 20 ms steps. After each trial participants were required to indicate whether the comparison stimulus had been *longer* or *shorter* than the standard. The position of the visual stimuli in the screen was manipulated resulting in three conditions:

1) central presentation of both standard and comparison stimuli,
2) right side presentation of standard and left side presentation of comparison stimuli,
3) left side presentation of standard and right side presentation of comparison stimuli. The results showed that the side of presentation affected participants' performance; when the comparison stimulus was presented on the right side participants gave more "longer" responses resulting in overestimations. In contrast, when the comparison stimulus appeared on the left participants gave more "shorter" responses resulting in underestimations. This finding was attributed to the role of a spatial representation of time oriented from left to right after the fashion of a typical number line where magnitude increases in the rightward direction.

Furthermore these results corroborate a body of evidence supporting the existence of local visual temporal mechanisms instead of a central supermodal clock. However, the effect of spatial position on temporal processing has been challenged by the results of some other studies that suggest a certain degree of independence between spatial and temporal processing. In Correa & Nobre's (2008) study, participants had to estimate either the size of a spatial gap or the duration of a temporal gap. Attention was manipulated via cues indicating that either a spatial or

temporal judgment is likely (though not guaranteed) to follow. The results of the study showed that attentional manipulation affected spatial and temporal judgments independently suggesting a degree of segregation between temporal and spatial resources.

In the present thesis, the duration discrimination paradigm was used in order to further examine the effect of spatial location on duration judgments. The first experiment was based on Vicario et al's (2008) study, which was described previously, extending the location manipulation to the auditory modality. Thus, the effect of right and left side of presentation was investigated in duration discrimination with visual and auditory stimuli. If the effect of location would be similar in the two sensory modalities this would support the existence of a central temporal mechanism, whereas if the location affects visual and auditory duration judgments differently, then this would further support the hypothesis of modality specific temporal mechanisms.

2.3 The Role of Spatial Attention in Temporal Judgments

2.3.1 Attentional models of timing and general effects of attention on timing

Several studies have shown that attention plays a crucial role in the subjective duration of events. A general finding in the research of time perception is that attention expands the perceived duration (New & Scholl, 2009; Coull, Vidal, Nazarian & Macar, 2004; Mattes & Ulrich, 1998). For example less frequent or

unexpected events are judged as longer in duration than more frequently occurring or expected events (Seifried & Ulrich, 2008). The oddball paradigm has often been used to examine this effect. It consists of requiring participants to respond to a low probability stimulus that occurs within a train of high probability stimuli (Tse, 2010; Tse, Intrilligator, Rivest & Cavanagh, 2004).

This dilation of the duration has been mainly attributed to the fact that unexpected stimuli attract attention. When more attention is dedicated to timing, then more pulses are counted (Casini & Macar, 1997). As a result, the attended intervals are judged as longer, according to clock models of temporal processing that focus on the role of attention such as the **attentional gate model** (Zakay, 1993; Block & Zakay, 1996). The attentional gate model complements the cognitive internal clock models by assuming the existence of an attention gate (switch) that opens for the timing of an event and closes at the end of the time period of the event.

The attentional gate model has also been used in order to interpret the temporal performance of participants in dual task conditions. When participants need to perform concurrently two different tasks, temporal judgements usually become shorter and more variable (Brown, 2010; Brown, 2008). For example, in Macar, Grondin & Casini‘s study (1994) participants were given two tasks; a temporal task and a non-temporal task, and were asked to allocate various proportions of attention to each component of the dual task. The results of the study demonstrated that when less controlled attention was dedicated to the temporal task then the temporal judgments became shorter and less precise. Hence, when attention is distracted from timing, more pulses are missed by the accumulator, resulting in the underestimation of duration.

Furthermore, it has been observed that dividing the attention between different properties of the same stimulus can induce an underestimation of the duration of the stimulus (Cicchini & Morrone, 2009). This observation is compatible with attentional models of timing. In fact, according to another attentional model of timing (**Thomas & Weaver model**) timing processes draw directly from the same finite attentional resources that other processes depend upon (Thomas & Weaver, 1975). Therefore, when a participant dedicates attention to other properties of the stimulus, less attention is available for the timer and so the duration is underestimated.

A recent meta-analysis of different temporal perception studies that manipulated tasks' cognitive load supported the finding that in cases of divided attention – as well as in other situations where there is high cognitive load – the duration judgments are decreasing (Block, Hanckock & Zakay, 2010). For example, task demands were shown to affect the reproduced duration of an interval with participants undereproducing the durations as the task difficulty increases (Brown & Boltz, 2002; Sawyer, Meyers & Huser, 1994).

2.3.2 Transient spatial attention effects on duration processing

Covert spatial attention – attending to an area in the periphery without directing the gaze towards it – can also affect temporal judgments by increasing the duration of brief peripheral stimuli (see Carrasco, 2006; Carrasco, Ling & Read, 2004, for covert spatial attention; Chen & O'Neill, 2001). Spatial attention is usually manipulated with attentional cues (Hein, Rolke & Ulrich, 2006); a common finding is that stimuli durations appear longer in cued locations than in un-cued locations.

A. Single task versus dual-task paradigms

Although a large number of studies exploring the effect of attention on temporal processing have been conducted, there are few studies that have directly manipulated transient attention. Transient (or exogenous) attention is a more automatic component and involves the involuntary orienting of attention to a location driven by sudden changes (Carrasco, 2006). Chen & O'Neill (2001) conducted a series of experiments manipulating both transient and sustained attention. They found that a briefly presented stimulus at the attended region was judged as longer than a stimulus at the unattended regions regardless of cueing type: exogenous luminance cue (manipulating participants' transient attention) or endogenous arrow cue (manipulating participants' sustained attention). An interesting result of this study is that the expansion of the duration of the attended locations was only observed when the duration judgment task was performed concurrently with another letter discrimination task. When the duration judgment was a single task the stimulus was judged as shorter when it appeared at the attended location; this finding suggested that the processing demands of a task can affect the attentional modulation of temporal judgments (Chen & O'Neill, 2001).

However, another study that directly manipulated participants' transient attention showed evidence for duration dilation of stimuli in attended locations even though the duration judgment was a single task (Yeshurun & Marom, 2008). In this study participants were sequentially presented with two discs. One of the discs was cued with a peripheral pre-cue indicating the disc location in advance, whereas the cue preceding the other disc did not indicate the location where it would appear. The

results of this study were interpreted in terms of a lengthening of the "internal response" that is generated for the attended stimulus.

This discrepancy between the results of Yeshurun & Marom (2008) (duration dilation in attended location in single task conditions) and the results of Chen & O'Neill (2001) (expansion of duration for attended locations only in dual task conditions) may be due to methodological differences. For instance, the visual display of Yeshurun & Marom's study was much simpler that Chen & O'Neill's one in order to avoid encouraging non-temporal processing. For this purpose, simple discs were used whereas in Chen & O'Neill's study the stimuli were letters (O and X). Moreover, the temporal task was different; while participants were performing a duration discrimination task (comparing the durations of two sequentially presented discs) in Yeshurun & Marom's study, in Chen & O'Neill's study participants were asked to perform a duration rating task of a single stimulus.

A recent study investigated further the effect of transient shifts of spatial attention in the subjective duration of brief intervals (Cicchini & Morrone, 2009). A dual-task procedure was used in this study involving a primary visual task and a secondary duration discrimination task. Participants were required to fixate on a central fixation point, with two laterally positioned circles. One of the circles changed size (either expanding or contracting) and the participants had to discriminate between the two sequences. The secondary task involved the presentation of two empty durations, each indicated by the interval between two brief presentations of an horizontal bar at either the top or bottom of the screen. The first interval, termed the test interval, was 430 ms in duration. The second interval, termed the probe interval, occurred 2-3 seconds later and varied randomly in duration

approximating the duration of the test interval. The participants were required to indicate whether the probe or the test interval seemed longer in duration.

The results showed that when the stimuli of the primary task were temporally close to or overlapped the empty test interval, then there was a considerable compression of duration. This compression was also proportional to the duration of the interval. A surprising finding of this study was that the distortion of the duration occurred only when the bars that were marking the empty intervals were presented in different locations. The effect disappeared when the bar indicating the end of the interval appeared in the same location as the bar indicating the beginning of the interval. In these trials the attentional manipulation did not influence the apparent duration, whereas when participants had to monitor two spatial locations and shift their attention between them a strong effect was observed.

These results were interpreted in terms of separate local temporal mechanisms. If different temporal mechanisms exist, monitoring independently various spatial locations, then in conditions of limited attentional resources – such as in a divided attention paradigm – there is an increased difficulty in comparing the outputs of separate clocks which as a result leads to biases in duration judgments. Therefore Cicchini & Morrone's (2009) findings seem to contribute to the body of evidence for spatially selective temporal mechanisms, such as the studies on adaptation and saccadic eye-movements that were mentioned earlier.

Spatial attention shifts played an important role in the present thesis, as most of the experiments required participants to discriminate between the durations of stimuli that appeared in different locations – laterally or horizontally positioned –

while fixating at the centre of the screen. Hence, this study concerned transient attention shifts. Furthermore, the presentation of visual and auditory trials as well as the number of spatial positions that stimuli appeared, were varied across experiments producing tasks with differential processing demands. Therefore, the effect of cognitive load and how it could potentially modulate the effects of modality and spatial location was also investigated.

2.4 Summary

This Chapter presented three crucial extra-temporal variables that have been shown to modulate judgments of brief durations and constitute the basis of the present work. It first explored the differences between visual and auditory timing and discussed the potential underlying mechanisms and the remaining open questions. It moved on to illustrate the close relationship between spatial and temporal processing and to present examples of studies that suggest the existence of spatially selective temporal mechanisms. The last section indicated the importance that attention plays in temporal processing, emphasizing the fact that it is not always clear under which circumstances it modulates the perceived duration. Experiments that were conducted during this PhD thesis, attempt to explore some of the open questions discussed in Chapter 2. They will be presented in the following two chapters.

Chapter 3 –

SPATIAL LOCATION EFFECTS ON VISUAL AND AUDITORY DURATION JUDGMENTS:

RIGHT VS LEFT PRESENTATION

This chapter presents four experiments exploring the effect of lateral stimulus location on duration judgments using the duration discrimination paradigm across visual and auditory modalities. These experiments attempt to answer some of the open questions that were discussed in Chapter 2: Is the right side of space indeed related to overestimations of duration and the left side to underestimations? Does the location of the stimuli affect visual and auditory judgments in the same way? How do differential processing demands interact with the spatial location on visual and auditory duration judgments?

3.1 General structure of methods – analysis

All the present experiments employed the reminder version of the duration discrimination paradigm (see Chapter 1, section 1.5.2.B) with filled auditory and visual intervals. As the present work focuses on sub-second timing – for which there is the most evidence for a relationship with spatial processing – all the stimuli that were used are within the range of a few hundred milliseconds (between 200 and 400 ms). Visual stimuli were presented on the right or the left side of the screen and auditory stimuli were presented monaurally to the left or right ear. The number of

spatial positions and the presentation of visual and auditory stimuli was varied across experiments, resulting in tasks with differential processing demands.

The first experiment involved the presentation of stimuli in two spatial location conditions and the presentation of visual and auditory trials in separate blocks. The second experiment had the same number of spatial location conditions as the first, but the different modality trials were intermixed. The third experiment involved the presentation of stimuli in four spatial location conditions with intermixed presentation of modality trials whereas the fourth experiment also involved four spatial location conditions but it was conducted only in the visual modality.

The instructions emphasized both the speed and accuracy of participants' performance. The importance of fixating on the centre of the screen was also emphasized as no controlled fixation was used (no use of chin rest or eye-tracker). However, participants reported that they found the task easier when they fixated on the centre than when moved their eyes. The analysis of the results was structured similarly across all the present experiments. Five different measures were used in each experiment in order to analyse participants' performance.

Firstly, **error percentages** were calculated by experimental condition (modality: visual – auditory*spatial location: 2 or 4 levels*duration of comparison stimulus: 10 levels), for each participant. An ANOVA was conducted on the mean error percentages with modality (for the experiments that involved both auditory and visual presentations), spatial location (with 2 or 4 levels depending on the experiment) and comparison stimulus duration (10 levels) as independent variables. A second ANOVA was then conducted with the same independent variables;

however the comparison stimulus duration was divided in two levels (instead of 10), shorter than 300 and longer than 300. In case of significant interactions between the independent variables additional ANOVAs or t-tests were conducted as appropriate.

The second measure was participants' **reaction times** – calculated from signal offset[1]. Mean reaction times were calculated for each participant, for each experimental condition[2]. The instructions at the beginning of each experiment emphasized both accuracy and speed of responses.[3] Thus, the relationship between reaction time and accuracy was investigated – considering that reaction time performance in duration discrimination has not previously been studied. The analysis of mean reaction times was the same as the analysis of mean error percentages.

The proportion of trials where participants had replied *longer* was then calculated for each participant, for each condition. An ANOVA was initially conducted on the mean **proportion of *longer* responses** with modality, location and comparison duration stimulus as independent variables. In the experiments that involved mixed modality presentation, two separate ANOVAs were then conducted, one for the visual and one for the auditory modality.

The individual **bisection points** and **Weber ratios** from the psychophysical function were then calculated (see Chapter 1, section 1.5.2.B, pp. 20-21). The bisection point is the point of subjective equality, i.e. the comparison duration that gives rise to 50% *longer* responses. The bisection point was calculated from the coefficients (slope and intercept) resulting from individual logistic regressions on the

[1] Values greater than two standard deviations above the mean were considered as outliers and were excluded.
[2] It has been argued that analysis of median RTs is more robust that of mean RTs (Whelan, 2008), and so we repeated the analysis using median RTs. However in our case the same effect was observed either way, so only the mean RTs analysis is reported.
[3] A previous experiment, which was part of a third year project, compared the performance on duration discrimination, when the instructions emphasised accuracy, versus when the instructions emphasised speed and found no effect.

proportion of *longer* responses (Droi-Volet, Tourret & Wearden, 2004). Dividing the slope by the intercept (b0/b1), produces the bisection point for each condition.

The Weber ratio, a measure of relative temporal sensitivity, results from the same individual logistic regressions on the proportion of *longer* responses. The Weber ratio is calculated by dividing the difference limen (half the difference between the comparison stimulus that gives rise to 75% of longer responses and the comparison stimulus that gives rise to 25% of longer responses) by the value of the bisection point. Lower values of the Weber ratio indicate higher temporal sensitivity (Droit-Volet & Rattat, 2006). An ANOVA was conducted on both bisection points and Weber ratios with modality and location as independent variables. In case of significant interactions, pair-wise t-tests were subsequently conducted as post-hoc tests.

3.2 Experiment 1 – Introduction

The right side of space has been found to be associated with longer duration judgments and the left side of space with shorter duration judgments, as was discussed in the previous chapter (see section 2.2.5). It has been suggested that this interaction between time and space is mediated by spatial attention (Frassinetti, Magnani & Oliveri, 2009). The initial aim of this experiment was to replicate Vicario et al.'s (2008) study (see section 2.2.5.*B*) in the visual modality and extend it to the auditory domain; would right monaural presentation tend to produce longer duration judgments and left monaural presentation shorter duration judgments? A similar effect of spatial presentation on both modalities would support a central amodal

timing mechanism whereas differential effects of space in vision and audition would indicate separate, modality specific mechanisms, as was mentioned in Chapter 2.

In the first experiment we examined the effects of spatial position on visual and auditory duration judgments, with visual and auditory trials presented in separate blocks. Filled circles were used for the visual stimuli and pure tones as the auditory stimuli. Visual and auditory trials were presented separately. The first interval of each trial was the constant standard, and the second was the variable comparison. Participants' task was to indicate if the second stimulus was shorter or longer in duration than the first one. The spatial position of stimuli varied, such that they were presented on the left or right side of the screen in the visual trials or monaurally, in the left or right ear in the auditory trials. For each trial, the second stimulus was always presented laterally opposite the first, resulting in two location conditions: first Right, second Left (**RL**) and first Left, second Right (**LR**).

Apart from the hypotheses about the effects of left and right presentation on perceived duration, an additional aim was the re-examination of the previously reported modality effect on perceived duration (see section 2.1.2). The main prediction here was that in this experiment with the blocked presentation of different modality trials no differences in perceived duration between visual and auditory judgments would be observed.

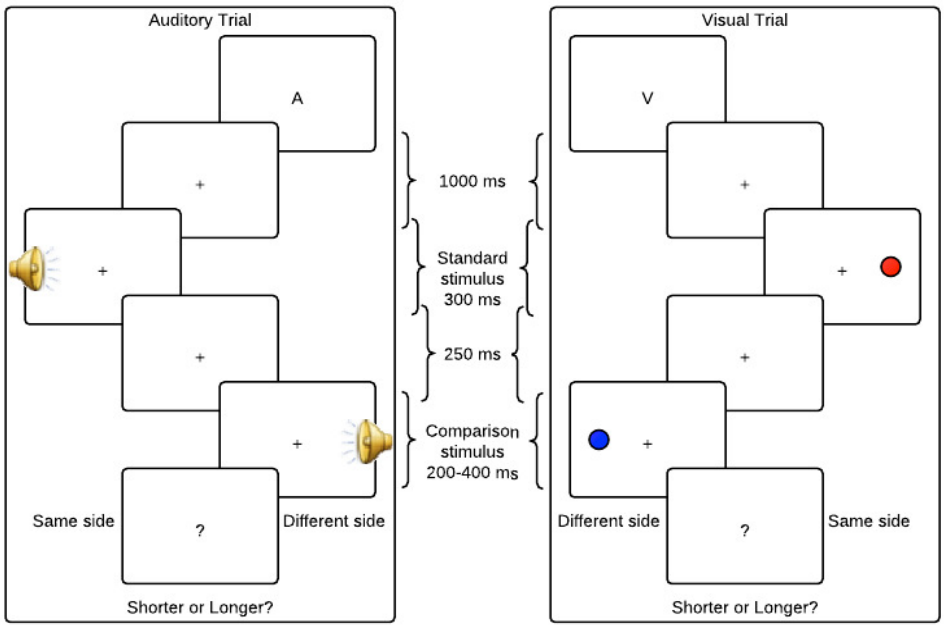


Figure 3.1 Time course & stimuli of Experiments 1 & 2

3.2.1 Methods

A. Participants

Fourteen female and eleven male students of the University of Edinburgh from 18 to 28 years in age (M = 24.6, SD = 3.9) participated in a single experimental session that lasted approximately 25 minutes. They were paid £5 for taking part in the experiment. All of them were right-handed and had normal hearing and normal or corrected-to-normal vision. The data of 3 participants were excluded from the analysis due to a high level of inaccurate responses (they scored with more errors than 2 standard deviations above the mean error performance of the group). Therefore, data from 22 participants were analysed.

B. Apparatus and Stimuli

A PC with a colour monitor controlled the presentation of the stimuli and it was located approximately 60 cm in front of the participants. The experimental program was designed in E-Prime 2, which assured millisecond accuracy for timing of stimuli and responses. The stimuli were filled visual or auditory intervals. The visual stimuli were blue or red circles, which were 1° in width, presented on the left or the right side of the screen (8° eccentricity) on a white background. The auditory stimuli were pure 440 Hz tones and were presented monaurally via headphones at an intensity of 75 dB SPL.

C. Procedure

At the beginning of the experiment participants were presented with the instructions, which emphasized the importance of fixating on the centre of the screen throughout the experiment. A visual trial started with the presentation of a fixation point (black cross) in the centre of the screen (see Figure 3.1). The fixation cross was displayed at the centre of screen throughout the trial. After 1000 ms, the standard stimulus (red circle on half of the participants and blue on the other half) was presented for 300 ms. Half the trials started with a left side presentation whilst the other half started with a right side presentation. The inter-stimulus interval (ISI) between the standard and the comparison was 250 ms. Ten different comparison durations were used, ranging from 200 ms to 400 ms with a constant step size of 20 ms, excluding 300 ms. The stimuli were either blue or red in colour, with the standard and comparison

always coloured differently from one another[4]. Thus randomly selected comparison had a 50/50 chance of being longer or shorter in duration than the standard. The comparison stimulus was always presented laterally opposite the preceding standard. This resulted in having two spatial position conditions, Left – Right (L-R) and Right – Left (R-L) with participants performing 160 trials with each condition. The different position trials were randomly intermixed. On the offset of the comparison stimulus a question mark appeared at the middle of the screen prompting participants to indicate whether the comparison has seemed shorter or longer than the standard by pressing either "m" or "k" on the computer keyboard. In total the visual block included 320 trials. After the end of the visual block participants were required to perform the auditory block. There was a rest period between blocks and the participants initiated the next block when they felt ready to proceed.

The structure of the auditory block was similar to the visual one. Instead of circles on the left and right side of the screen participants were presented with a tone to either the left or right ear. Again participants were performing 320 auditory trials. Participants were always presented with the visual block first in order to reduce the chance of using strategies based on imagining sounds corresponding with the circles (Guttman, Gilroy & Blake, 2005).

Twenty practice trials preceded each block. Participants were given a short break in the middle of each block. A single session consisted of 40 practice trials and 640 experimental trials in total.

[4] The different colours were used in order to prevent participants from perceiving temporal overlap between the standard and comparison stimuli.

3.2.2 Results

A. Error percentages

The percentages of errors were calculated for each experimental condition. The mean percentage of errors was 25.7% in visual blocks and 14% in auditory blocks. A repeated measures ANOVA was conducted with modality, location and comparison stimulus duration as independent variables. The effect of modality on errors was significant, ($F(1,21)=47.6$, $p<0.001$) indicating that stimuli were better discriminated in the auditory modality. The effect of duration was also significant, ($F(2.5,52.7)=33.1$, $p<0.001$). Also the interaction between modality and duration was significant, ($F(4.6,97.6)=2.8$,$p<.05$). Mauchly's test indicated that the assumption of sphericity had been violated ($x^2(65) = 150.2$, $p<.05$); therefore degrees of freedom were corrected using Greenhouse – Geisser estimates of sphericity ($\varepsilon=.288$). No effect of location was found. Error rates increased with proximity of the comparison duration to the standard duration, peaking at 280 ms. We wanted to investigate any potential differences in participants' performance between shorter and longer than the standard duration ranges; thus, we conducted another ANOVA with modality, location and duration as independent measures. However in this analysis we considered the comparison durations as two categories: shorter than 300 ms and longer than 300 ms (instead of ten separate items). Only the modality by duration interaction was found to be significant, ($F(1,21)=6.1$, $p<.05$). Inspection of Figure 3.2 indicates that although in the visual modality, there is no difference between shorter and longer range (24,9% versus 26,4%), in the auditory less errors are committed in the longer range (11%) than in the shorter range (17%). This observation was

confirmed by an ANOVA in the auditory modality with two factors, location and duration range. The effect of duration range was indeed significant, ($F(1,21)=6.2$, $p<.05$).

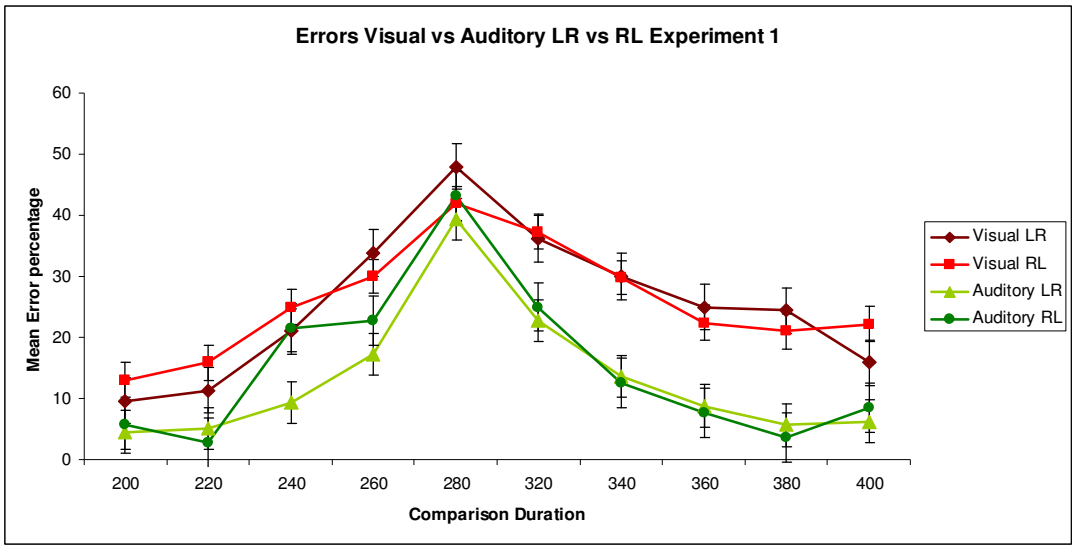
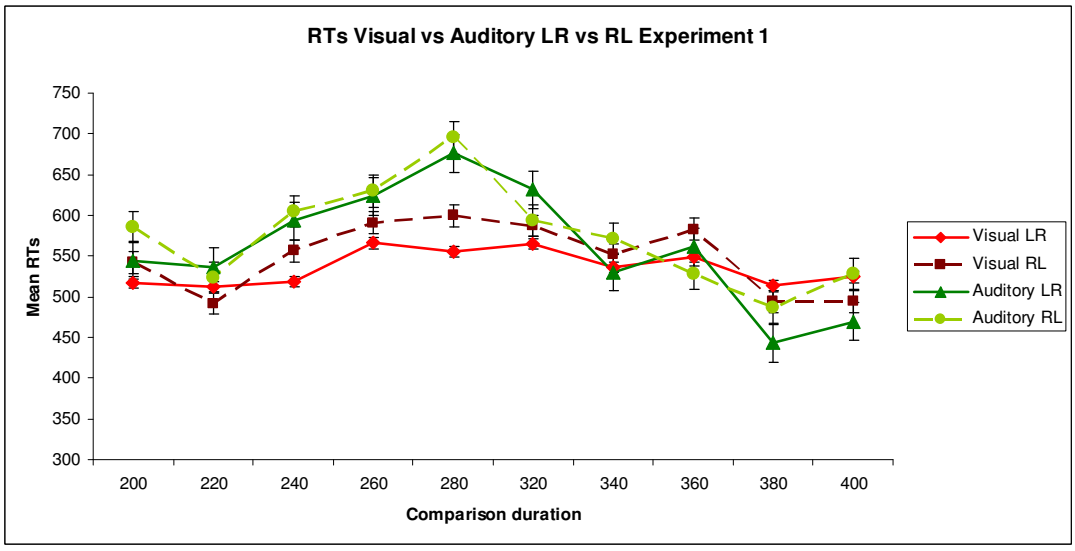


Figure 3.2. Mean Error percentages from the auditory and visual conditions of Experiment 1. Error bars are SEM (standard error of the mean).



Figures 3.3. Mean reaction times from the auditory and visual conditions of Experiment 1.

B. Reaction times

Reaction times – calculated from signal offset – were recorded and analysed. Reaction times were similar between visual and auditory blocks (542 ms and 567 ms respectively). This observation was confirmed by the statistical analysis. A repeated measure ANOVA with three factors (modality, location & duration) was conducted on participants' reaction times. Only the main effect of duration was found to be significant, ($F(3.1,65.4)=10.6$, $p<.001$) as well as the interaction between duration and modality, ($F(4.8,102)=3$, $p<.05$). Figure 3.3 shows the reaction times of participants in visual and auditory modalities across the duration of the comparison stimulus. Reaction times appeared to be slightly shorter when comparison duration was longer than the standard. In order to examine if this observation was accurate we conducted an additional ANOVA with modality, location and duration as independent measures. For this analysis we again considered the ten comparison durations as two categories: longer than 300 ms or shorter than 300 ms. In this analysis, we found a significant effect of duration, ($F(1,21)=4.4$, $p<.05$), suggesting that participants were faster when the comparison duration was longer than the target one (537 ms) than when it was shorter (573 ms). The interaction between modality and duration was also significant, ($F(1,21)=7.6$, $p<.05$). Two ANOVAs , one for each modality were conducted in order to investigate the above interaction; Whereas in the visual modality the effect of duration was not significant, suggesting that there were no significant differences between the two duration ranges (545 ms for the shorter range versus 539 ms for the longer range), in the auditory modality the duration effect was found to be significant, ($F(1,21)=11.4$, $p<.01$) with participants being faster in the longer range (534 ms) than in the shorter range (601 ms).

C. Psychophysical functions

The proportion of trials on which participants judged the duration of the comparison stimulus to be longer than the standard was calculated. Figure 3.4 shows the mean proportion of *longer* responses plotted against the durations of the comparison stimulus in the different modalities and the different location conditions. Inspection of the Figure 3.4 indicates that the slope was flatter for the visual condition than for the auditory. When all factors were considered together, repeated measures ANOVA found effects of comparison stimulus duration, ($F(2.36,49.65)=232.35$, $p<.001$), and a significant modality by stimulus duration interaction, ($F(2.47,51.88)=18.9$, $p<.001$). As this overall analysis is somewhat uninformative about any specific effect of location, separate repeated measures ANOVAs in the Visual and Auditory modality were conducted. Only duration was found to have a significant effect in either visual or auditory comparisons, Visual, ($F(1.8,39.2)=58.31$, $p<.001$) and Auditory, ($F(3.3,69.7)=319.17$, $p<.001$). As expected, increasing the duration of the comparison interval increased the proportion of *longer* responses.

The individual bisection points and Weber ratios from the psychophysical functions were also calculated. The resulting bisection point values for the different experimental conditions are shown in Table 1. It seems that the bisection points from the different experimental conditions were similar and also close to the arithmetic mid-point of the duration range used. Indeed, the ANOVA performed on the bisection points did not find significant effect of either modality or position.

The Weber ratio values for the different experimental conditions are shown in Table 3.1. Inspection of these values shows that although Weber ratios from the different position conditions within the same modality are identical, the Weber ratios

between modalities are very different. This effect of modality on Weber ratios was confirmed by a repeated measures ANOVA. The ANOVA showed a main effect of modality, ($F(1,21)=12.46$, $p<.05$). This difference is consistent with findings in previous studies on duration discrimination where the Weber ratio was larger for the visual than for the auditory modality (Lapid, Ulrich & Rammsayer, 2009; Ulrich, Nitschke & Rammsayer, 2006).

Table 3.1. Bisection points (BP) and Weber ratios (WR) from Experiment 1

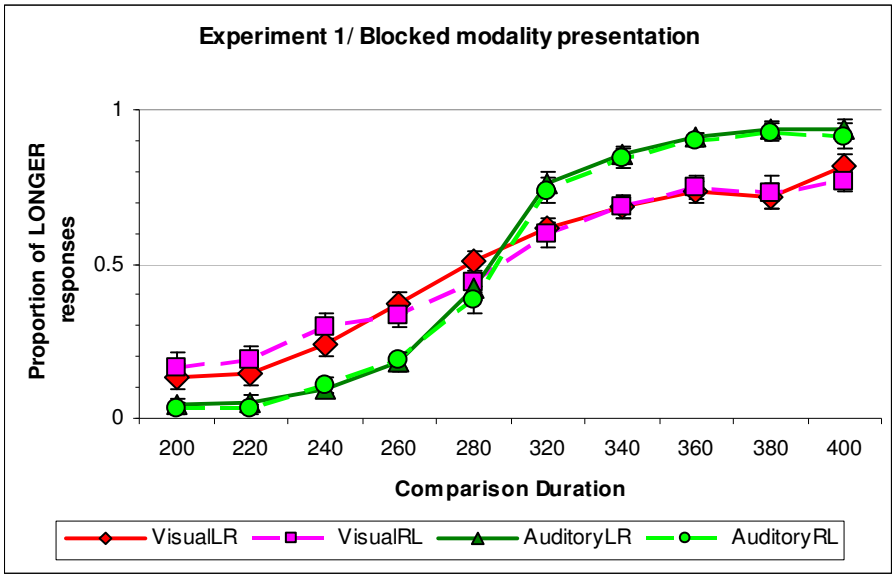
Condition		BP (mean)	WR (mean)
Visual	LR	299	0.085
	RL	304	0.084
Auditory	LR	294	0.042
	RL	297	0.044

3.2.3 Interim Discussion of Experiment 1

Participants performed with higher accuracy and exhibited higher temporal sensitivity in the auditory block than in the visual one. The modality difference in the proportion of longer responses was not observed here; this finding is not surprising as visual and auditory trials were presented in separate blocks. In Experiment 2 visual and auditory trials were presented intermixed in order to determine whether the modality effect on subjective duration also occurs when the location of the stimuli changes.

No effect of position was observed – in any of the measures – in either modality; this finding did not support the hypothesis that performance would differ with lateral positioning in the visual trials and contradicted the results of Vicario et

al., 2008. The fact that there were no differences between right and left presentation was quite surprising as the design of the present experiment kept very close to Vicario et al's original experiment. Therefore, an additional experiment was conducted in order to further investigate the effects of location on duration discrimination.



Figures 3.4. Psychophysical functions (mean proportion of *longer* responses plotted against comparison stimulus duration) from the auditory and visual condition of Experiment 1.

3.3 Experiment 2 – Introduction

Experiment 2 tested whether having intermixed presentation of visual and auditory trials would affect the psychophysical functions in the two different modalities; particularly if the mixed presentation would result in a higher proportion of "longer" responses in the auditory trials. Furthermore, as the different modality trials were intermixed the task should be more demanding than the previous one. Thus, the aim was to examine if this increase in demands would affect participants' performance

and if we could detect any effect of position presentation that we did not observe in the previous experiment. Experiment 2 had exactly the same structure as Experiment 1 except that the visual and auditory trials were not presented to the participants in different blocks but they were randomly intermixed.

3.3.1 Methods

A. Participants

Thirteen female and eleven male students of the University of Edinburgh from 18 to 28 years in age (M = 23.8, SD = 3.2) participated in a single experimental session that lasted approximately 30 minutes. They were paid £5 for taking part in the experiment. All of them were right-handed and had normal hearing and normal or corrected-to-normal vision. The data of 2 participants were excluded from the analysis due to high level of inaccurate responses. Therefore, data from 22 participants were analysed.

B. Apparatus and Stimuli

The apparatus was the same as in Experiment 1.

C. Procedure

The structure of this experiment was almost the same as in the Experiment 1. The only difference was that as the different modality trials were randomly intermixed, each trial started with a cue, which indicated to the participant the modality of the

imminent trial. A capital “V” was the cue for a visual trial and a capital “A” the cue for an auditory one. The cue remained on the screen for 1000 ms.

3.3.2 Results

A. Error percentages

The percentages of errors were calculated for each experimental condition. The average error rate was 24% for visual trials and 10.7% for auditory trials. Figure 3.5 shows the errors of participants in visual and auditory modalities across comparison duration. A repeated measures ANOVA was conducted with modality, location and duration of the comparison stimulus as factors. The ANOVA found a significant effect of modality, ($F(1,21)=97.7$, $p<.001$) and duration, ($F(2.3,50.3)=52.5$, $p<.001$). Also the interaction between modality and duration was significant, ($F(2.7,58)=5.9$, $p<.01$). In order to further investigate the effect of duration between shorter and longer (compared to the standard) durations we conducted an ANOVA with again modality, location and duration as independent measures. However in this analysis the duration instead of 10 had 2 levels (shorter than 300 and longer than 300 durations). The ANOVA showed a significant effect of duration, ($F(1,21)=4.9$, $p<.05$) suggesting that participants were making significantly less errors when the target duration was longer than 300 (15.4%) than when it was shorter (20%). There was also a significant interaction between duration and modality, ($F(1,21)=5.9$, $p<.05$). Two additional ANOVAs were conducted in visual and auditory modality separately. The effect of duration was found to be significant only in the Visual modality, ($F(1,21)=8.4$, $p<.01$) (shorter range: 29% versus longer range: 20%). In the

auditory modality the percentages of errors were identical between shorter and longer range (10,7%).

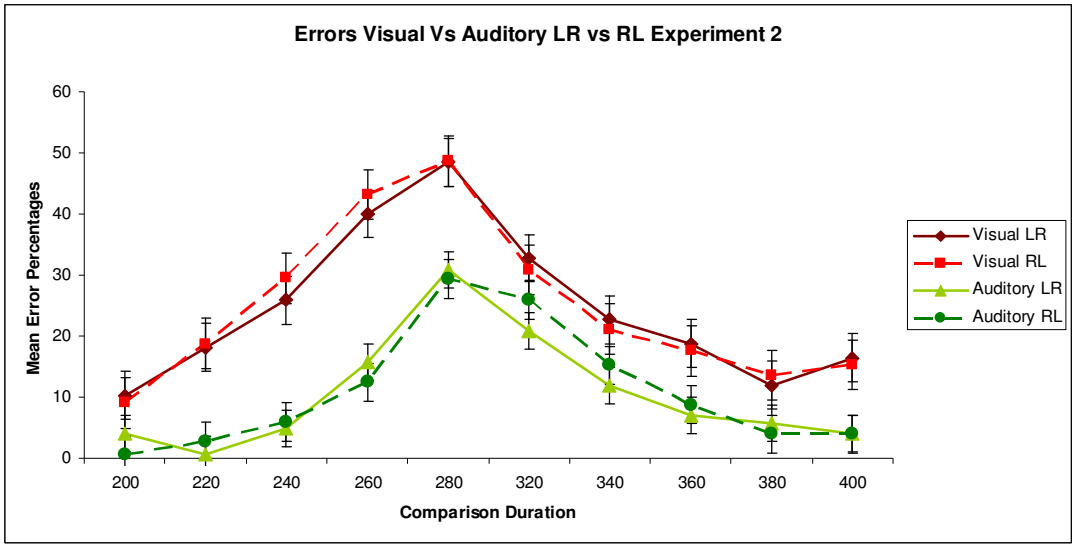


Figure 3.5. Mean Error percentages from the auditory and visual conditions of Experiment 2.

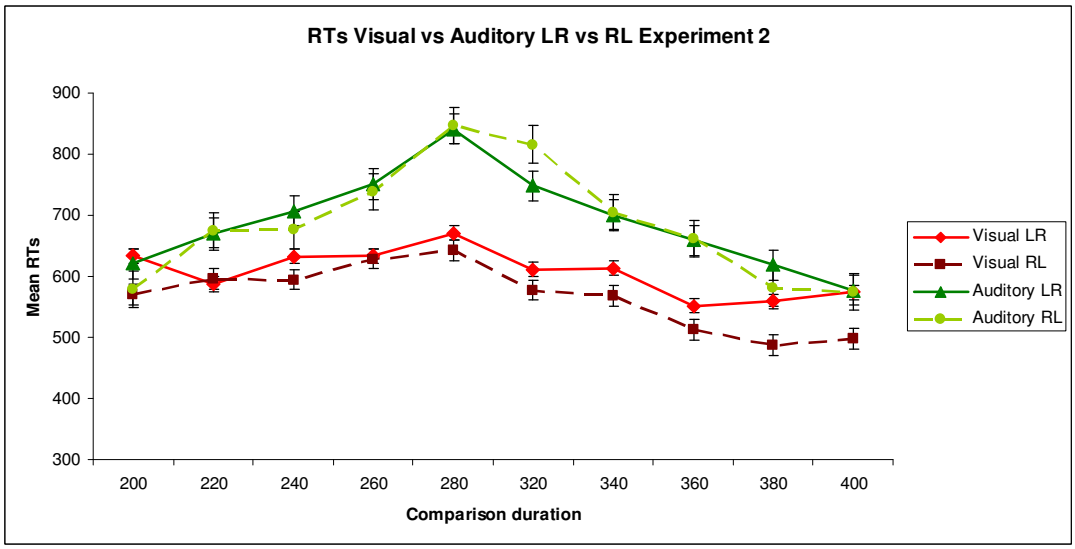


Figure 3.6. Mean reaction times from the auditory and visual conditions of Experiment 2.

B. Reaction times

Mean reaction times were 587 ms for the visual trials and 687 ms for the auditory trials. In the Experiment 2 it seems that there is a difference between the reaction

times in visual and auditory trials with auditory reaction times being slower than the visual ones, a finding that seems to be against previous results where a temporal generalization task was used (N'Diaye, Ragot, Garnero & Pouthas, 2004). This observation was confirmed by statistical analysis. A repeated measures ANOVA with three factors (modality, location and duration) was conducted. There was a significant effect of modality, ($F(1,21)=18.5$, $p<.001$) and of duration, ($F(4.6,98)=13.8$, $p<.001$). The effect of location was also significant, ($F(1,21)=5.8$, $p<.05$) suggesting that participants were slightly slower in the LR condition (648 ms) than in RL (626 ms). The interactions between modality and duration, ($F(9,189)=5$, $p<.001$) and between modality and location, ($F(1,21)=5.6$, $p<.05$) were significant. In order to further investigate the effect of duration we conducted another ANOVA on participants' shorter and longer than the standard stimulus durations. Apart from the modality and location effects, the effect of duration was found to be significant, ($F(1,21)=16.3$, $p<.001$) with participants being slower when the comparison stimulus was shorter than the standard (664.5 ms) compared to when it was longer (610 ms). Two additional ANOVAs were conducted in visual and auditory modality separately. In both, duration was found to have a significant effect, ($F(1,21)=13.7$, $p<.001$) for visual and ($F(1,21)=6.9$, $p<.05$) for the auditory. The difference between shorter and longer durations was slightly larger for the visual (shorter range: 619 ms – longer range; 555 ms = 64 ms difference) than for the auditory (shorter range: 710 ms – longer range: 663 ms = 47 ms difference). Also, the effect of location was found to be significant only for the visual modality, ($F(1,21)=10.7$, $p<.01$) (LR = 607 ms, RL =567 ms). Figure 3.6 suggests that this effect of location is more prominent in the longer range. Thus, two further ANOVAs were conducted, one in the shorter

duration range and one in the longer duration range. There was a trend for an effect of location only in the longer range, ($F(1,21)=3.8$, $p=.062$).

C. Psychophysical functions

Figure 3.7 shows the psychophysical functions in the visual and auditory trials. Inspection of this Figure suggests that the proportion of *longer* responses increases with comparison stimulus duration, but again the slope for the visual condition was flatter than the auditory one. A repeated measures ANOVA was conducted with three factors (modality, location, duration). The ANOVA found effects of modality, ($F(1, 21)=5.04$, $p<.05$) and stimulus duration, ($F(2.17, 45.5)=424.65$, $p<.001$). The visual trials contained a higher proportion of *longer* responses. Also the interaction between modality and duration was found to be significant, ($F(4.07, 85.6)=36.01$, $p<.001$). Separate repeated measures ANOVAs in the visual and auditory modality were thus conducted. In both only the effect of duration was found to be significant, for visual, ($F(2.23 ,46.8)=130.57$, $p<.001$) and for auditory, ($F(3.07 ,64.62)=585.35$, $p<.001$).

In order to further investigate the differences between the psychophysical functions in the different conditions, the individual bisection points and Weber ratios were calculated. The resulting bisection points for the different experimental conditions are shown in Table 3.2. Inspection of the values in Table 3.2 reveals that the bisection points were similar within the same modality conditions. However, it seems that there is a difference between modalities with auditory bisection points having larger values than visual. This difference suggests an overestimation of visual durations compared to the auditory ones. A repeated measures ANOVA with modality and location as factors showed in fact a significant effect of modality,

(F(1,21)=5.93. p<.05). This modality effect in the present experiments seems to have the opposite direction than in previous studies. T-tests showed that visual RL was significantly smaller than auditory RL, (t(21)=-2.65, p<.01) and there was a trend for visual LR to be smaller than the auditory LR, (t(21)=-2.02, p=.076). This difference suggests that participants tended to overestimate the visual trials. According to previous experiments that presented intermixed visual and auditory trials, participants should overestimate the auditory trials and not the visual ones. Figure 3.8 shows the bisection points for Experiments 1 & 2.

The Weber ratio values are also shown in Table 3.2. As in the Experiment 1, the Weber ratios between modalities are very different. This effect was confirmed by a repeated measures ANOVA that showed a significant effect of modality, (F(1,21)=24.36, p<.001). Therefore, again participants had higher temporal sensitivity in the auditory modality. Also, the Weber ratios were very similar to the Weber ratios in Experiment 1.

Table 3.2. Bisection points (BP) and Weber ratios (WR) from Experiment 2

Condition		BP (mean)	WR (mean)
Visual	LR	286*	0.084
	RL	283**	0.091
Auditory	LR	296	0.034
	RL	301	0.035

*p<0.05 significant overestimation, **p<0.01 significant overestimation

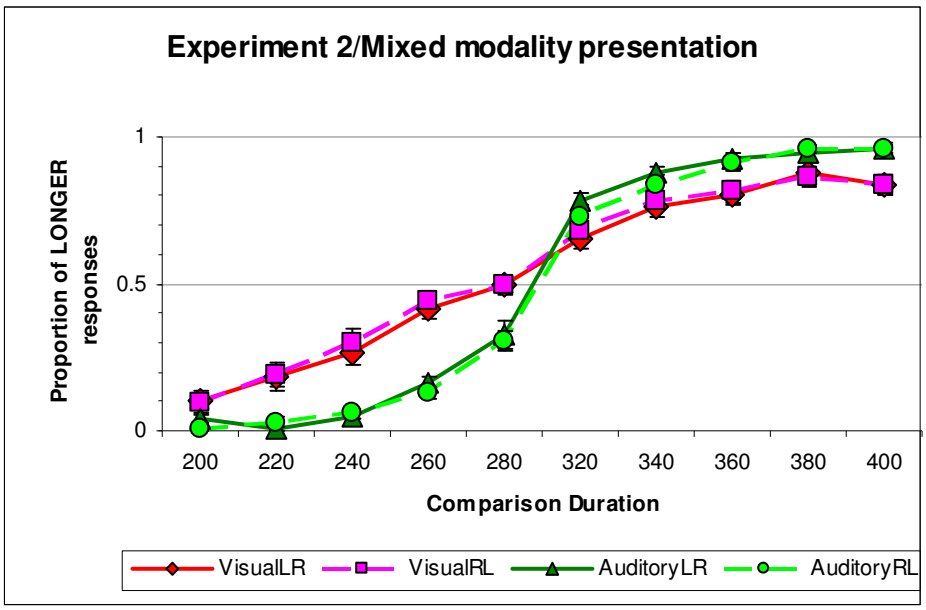


Figure 3.7. Psychophysical functions (mean proportion of *longer* responses plotted against comparison stimulus duration) from the auditory and visual condition of Experiment 2. A leftward displacement of the visual functions on the 0.5 point indicates participants' overestimation of visual trials.

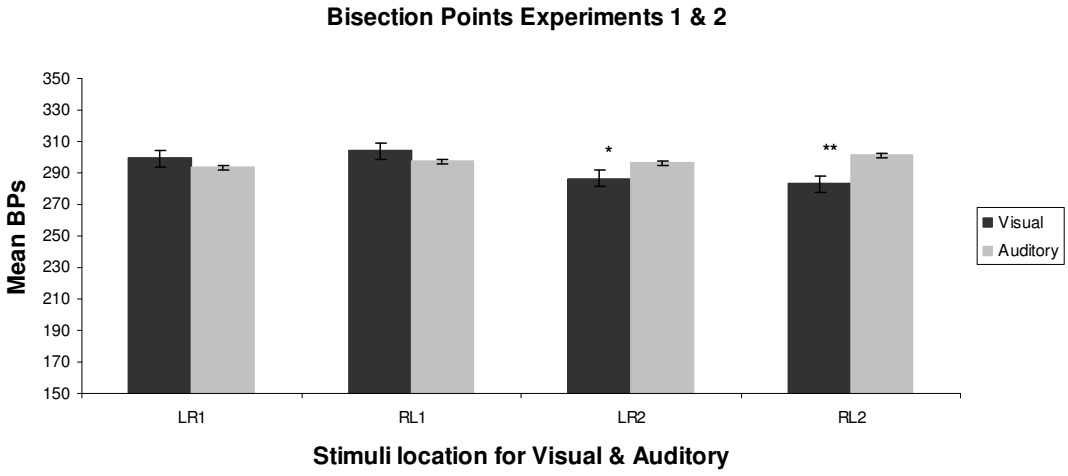


Figure 3.8. Bisection points for Experiments 1 & 2. Although participants' visual and auditory bisection points did not differ significantly in Experiment 1 (LR1 & RL1), in Experiment 2 participants were overestimating the visual trials in comparison to the auditory (LR 2 & RL2).

3.3.3 Interim Discussion of Experiment 2

In Experiment 2 participants had higher temporal sensitivity in the auditory modality than in the visual one, as in Experiment 1. Also, there was no effect of right and left spatial presentation in either modality. In this experiment, as the visual – auditory trials were intermixed, we were expecting to notice longer judgments of auditory trials, as previously reported (Wearden, Todd, & Jones, 2006). However, we observed exactly the opposite pattern: participants tended to overestimate the visual trials in comparison to the auditory ones. The location of stimuli presentation is a major difference between the present study and the previous studies that have examined visual and auditory differences in temporal judgments. In contrast to the previous studies that involved central presentation of visual stimuli and binaural presentation of sounds, in the current study the visual stimuli were either on the left or on the right side and the second stimulus was always positioned opposite the first one. In this case participants needed to monitor two separate locations and to shift their attention between two locations. So, this result could be attributed to the transient shifts of spatial attention between the two stimuli. Previous research has shown that attentional factors often play an important role in time perception (Pouthas & Perbal, 2004). When more attention is dedicated to temporal processing more pulses are counted and therefore the duration is often overestimated. It is conceivable that the change of position of the visual stimuli causes participants to attend more to the second stimuli and therefore an overestimation bias is observed. In order to test this hypothesis, we conducted a third experiment, which involved two additional spatial positions.

A surprising finding concerns the reaction time performance of participants in the current experiment. Participants were found to exhibit significantly different reaction times between modalities. Specifically, participants were slower in auditory trials compared to visual ones (by approximately 100 ms on average). This result seems to be in contrast to previous results coming from a temporal generalization task (N'Diaye, Ragot, Garnero & Pouthas, 2004) where participants were both more accurate and faster in the auditory modality than in the visual one. Also, reaction times for auditory stimuli are generally faster (about 140-160 ms) than reaction times for visual stimuli (about 180-200 ms). In the present study, difference in reaction times between modalities appeared only when the visual and auditory trials were presented intermixed. In the experiment where trials were blocked by modality, differences in reaction times were not observed. Furthermore, in the present experiment both visual and auditory reaction times were faster in the longer than in the shorter range, which is contrast to Experiment 1 where only auditory RTs were significantly faster in the longer range.

Hence, this experiment still leaves a number of open questions that were further investigated in the following experiment.

3.4 Experiment 3 – Introduction

In Experiment 3 two new location conditions were added. When the first stimulus was presented on the left side the second could appear either on the left or on the right side and when the first stimulus was presented on the right side the second could appear either on the right or left side of the screen (or the right or left ear

respectively for auditory stimuli). Figure 3.9 presents the time course of Experiment 3.

Therefore, the participants did not know if the second stimulus was going to appear on the same or in a different position in contrast to the previous experiments where the second stimulus always appeared on the opposite side. This manipulation was expected to increase the attentional demands of the task as uncertainty about the location was added at the mixed modality blocks; the aim was to investigate if this would influence the effect of modality on the psychophysical functions. If spatial attention shifts do affect the performance then participants would be expected to perform differently between *same* and *change location* trials. Although in the *change of location* trials participants would still overestimate the visual stimuli in comparison to the auditory, in the *same location* trials, no differences or the opposite effect would be anticipated. Moreover, although no effect of location per se was observed in the previous experiments, an additional aim was to investigate whether increasing the number of locations would reveal an effect of right or left spatial presentation.

The final question concerned the reaction time performance: Would the unexpected effect of faster visual reaction times be replicated in the following, more demanding experiment?

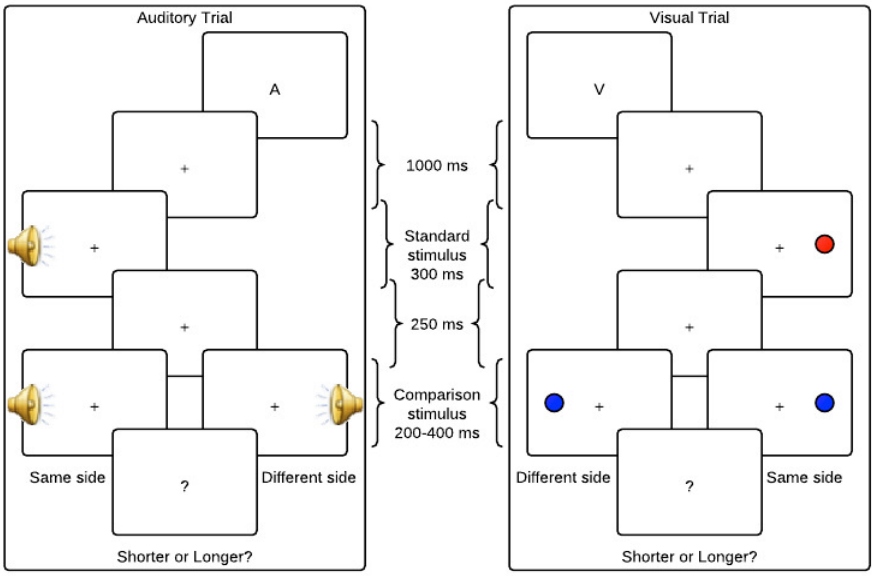


Figure 3.9. Time course & stimuli of experiment 3.

3.4.1 Methods

A. Participants

Fifteen female and thirteen male students of the University of Edinburgh from 18 to 29 years in age (M = 24.9, SD = 2.8) participated in a single experimental session that lasted approximately 50 minutes. They were paid £7 pounds for taking part in the experiment. All of them were right-handed and had normal hearing and normal or corrected-to-normal vision. The data of 4 participants were excluded from the analysis due to high level of inaccurate responses (they scored with more errors than 2 standard deviations above the mean error performance of the group). Therefore, data from 24 participants were analysed.

B. Apparatus and Stimuli

The apparatus was the same as in Experiments 1 and 2.

C. Procedure

The structure of Experiment 3 was similar to the structure of the previous experiment. The procedure differed during the stage of the presentation of the variable comparison stimulus. The comparison stimulus was presented in half of the trials on the same side of the screen (or at the same ear) as the presentation of the standard stimulus and on the opposite side (or different ear) in the other trials. This resulted in having four levels of spatial position for each modality, Left – Left (L-L), Left-Right (L-R), Right-Right (R-R), Right-Left (R-L). These different position trials were randomly intermixed and presented to the participants. Participants performed 80 trials on each level – a total of 640 trials. Participants had three breaks during the experimental session in order to rest.

3.4.2 Results

The error and reaction time analysis did not show any differences between the location conditions LR & RL or between the location conditions RR & LL. Thus, LR & RL data are combined and referred to as *change of location* condition and the RR & LL data are combined and referred to as *same location* condition. The results from these combined location conditions are presented below.

A. Error percentages

The average error rate was 26.3% for visual trials and 12.6% for auditory trials. A repeated measures ANOVA was conducted with modality, location (same vs change) and duration of the comparison stimulus as factors. The ANOVA found a significant effect of modality, ($F(1, 23)=119.24$, $p<.001$) and duration, ($F(2.27, 52.25)=47.33$, $p<.001$). Also the interactions between modality and duration ($F(2.85, 65.7)=6$, $p<.001$) and between location and duration, ($F(3, 70.6)=14.6$, $p<.001$) were significant. Inspection of Figure 3.10 suggests that there is a difference in performance between shorter and longer duration ranges in the visual *change of location* condition, whereas there is less difference between the shorter and longer ranges in visual *same location* and auditory conditions.

In order to further investigate this observation two additional ANOVAs were conducted, one for visual and one for auditory with two factors: location (same versus change) and duration with two levels (shorter versus longer). Although in the auditory modality no significant differences were revealed, in the visual modality a trend for a main effect of duration, ($F(1, 23)=3.4$, $p=.078$), was observed – indicating a higher percentage of errors in the shorter range (29%) than in the longer range (23.5%), and a significant interaction between location and duration, ($F(1, 23) =27.6$, $p<.001$). This interaction indicates that although in the shorter range participants make more errors in the *change of location* condition (36,2%) compared to the *same location* condition (22%), in the longer range the opposite pattern is observed with participants making more errors in the *same location* condition (30,67%) than in the *change of location* condition (16.4%) (see also Table 3.5 for mean percentages of errors across the different conditions). These differences were confirmed by t-tests

conducted as post-hoc tests, for the shorter range, ($t(23)=-3.1$, $p<.05$) and for the longer range, ($t(23)=5.3$, $p<.001$).

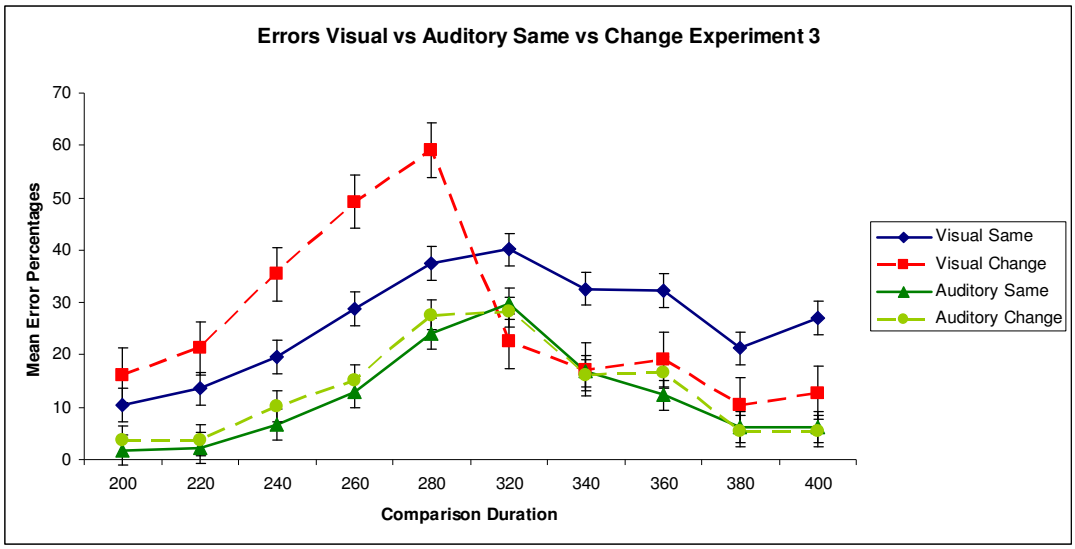


Figure 3.10. Mean Error percentages plotted against comparison stimulus duration from visual and auditory trials and comparing the performance between *same location* (RR – LL) and *change of location* (LR – RL) conditions.

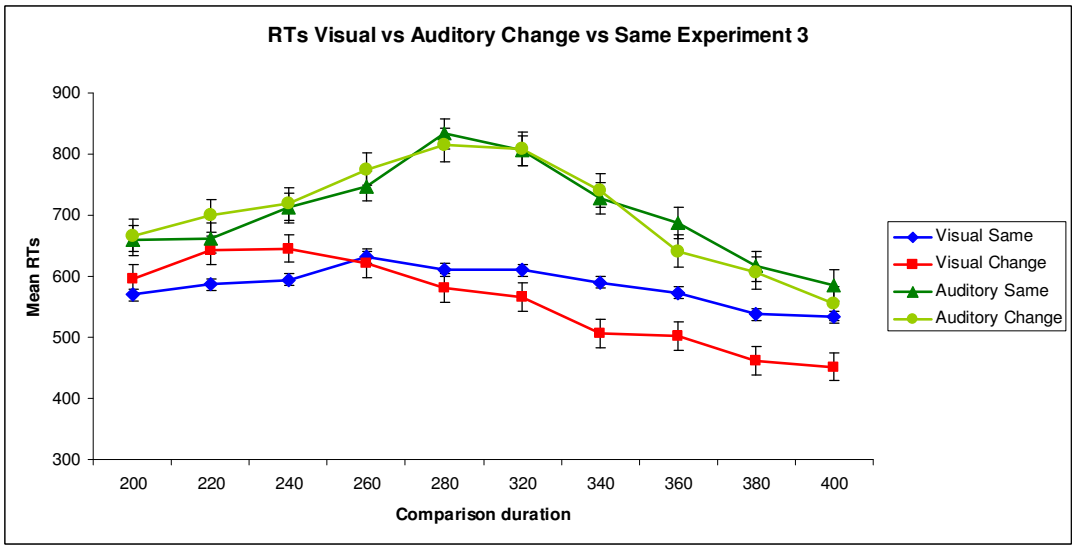


Figure 3.11. Mean Reaction times plotted against comparison stimulus duration from visual and auditory trials and comparing the performance between same location (RR – LL) and change of location (LR – RL) conditions.

B. Reaction times

Participants' average reaction times in this experiment were 570 ms for the visual trials and 703 ms for the auditory trials. Like Experiment 2, participants' reaction times in this experiment appear to be faster for visual than for auditory trials. This observation was confirmed by the analysis. A repeated measures ANOVA with three factors (modality, location and duration) was conducted revealing a significant effect of modality, ($F(1,23)=43.4$, $p<.001$) and of duration, ($F(3.8,87.6)=16.9$, $p<.001$), a significant interaction between modality and duration, ($F(3.9,90)=4.8$, $p<.001$) and a significant interaction between location and duration, ($F(4.9,113.5)=3.1$, $p<.05$). Figure 3.11 indicates a different pattern of performance in reaction times between shorter and longer duration ranges.

In order to further investigate these differences, an additional ANOVA was conducted, with the same factors, modality, location (same versus change) and duration with two levels (shorter versus longer) instead of ten. Apart from the effect of modality, the effect of duration range was also significant, ($F(1,23)=15.4$, $p<.001$) indicating slower RTs for the shorter range (668 ms) than for the longer range (605 ms). Also the interaction between location and duration, ($F(1,23)=8.1$,$p<.01$) was found to be significant, suggesting a larger difference between shorter and longer ranges for the change of location condition than for the same location condition. Finally, also the three way interactions between modality, location and duration were significant, ($F(1,23)=4.6$, $p<.05$).

In order to further investigate this three-way interaction separate ANOVAs were conducted, one for each modality, with two factors: location (same versus change) and duration (shorter versus longer). The ANOVA in the visual modality

showed a significant main effect of duration, ($F(1,23)=21.8$, $p<.001$) (shorter range: 607 ms versus longer range: 533 ms) and an interaction between location and duration, ($F(1,23)=11.1$,$p<.01$). This interaction indicated that the effect of duration range was larger for the change of location conditions (shorter: 617 ms – longer: 497 ms = 120 ms) than for the same location conditions (shorter; 598 ms – longer: 568 ms = 30 ms) (see also Table 3.5 for mean RT values across the different conditions). These differences were confirmed by t-tests conducted as post-hoc tests. Only the t-test for the change of location range was found to be significant, $t(23)=5.9$, $p<.001$).

In the auditory modality only a trend for an effect of duration was observed, ($F(1,23)=3.5$, $p=.071$) with participants being faster in the longer range (677 ms) than in the shorter range (728 ms) (50 ms difference).

C. Psychophysical functions

Figure 3.12 shows the psychophysical functions in the visual and auditory trials with same location (RR & LL) trials being combined and different location (LR & RL) trials being combined – the combined presentation of the above location conditions is due to the fact that there was no significant difference between left and right locations, but only difference between *same location* and *change of location* conditions. A slight rightward displacement of the visual function is apparent. A repeated measures ANOVA was conducted with modality, location and duration as factors. The ANOVA found main effects of modality, ($F(1,23)=5.28$, $p<.001$), location, ($F(1.71,39.4)=21.17$), $p<.001$ and duration, ($F(2.9,67)=483.4$, $p<.001$) and a significant interaction between modality and location, ($F(4.8,110.78)=48.17$, $p<.001$). The effect of location seems to only be present in the visual modality. Also,

it seems that participants have higher proportion of *longer* responses in the *change location* trials compared with the *same location* trials. Separate repeated measures ANOVAs were conducted for visual and auditory modality to confirm these observations. The analysis in the visual modality found an effect of stimulus location, ($F(1.68,38.66)=21.38$, $p<.001$), an effect of comparison duration, ($F(2.89,66.47)=146$, $p<.001$) and a significant location by duration interaction, ($F(12,276.3)=2.14$, $p<.05$). Pair-wise comparisons between the different location conditions showed significant differences between RR and LR and RR and RL. Also LL was significantly different than LR and RL but similar to RR. Participants in the conditions LR and RL, where the location of the comparison stimulus was different than the location of the standard, had higher proportion of *longer* responses compared with the RR and LL conditions, where the location of the first and second stimuli was the same. In the auditory modality only the effect of duration was significant, ($F(3.7,85.5)=566.9$, $p<.001$).

The effect of modality was also explored separately within the *same location* trials and within the *change location* trials. A repeated measures ANOVA performed on the *change location* trials showed a main effect of modality, ($F(1,23)=22.48$, $p<.001$) with participants giving longer judgments in the visual than in the auditory trials. The effect of modality was not significant in the *same location* trials.

Bisection points and Weber ratios for Experiment 3 are shown in Table 3.3. As in Experiment 2 visual bisection points in conditions LR and RL are displaced to the left of the standard duration value, showing an overestimation of durations. The auditory bisection points are larger than the visual in these two conditions and closer to the standard. However, it seems that there is a difference between these two visual

locations and the visual conditions RR and LL. The bisection points for RR and LL are displaced to the right of the standard. The within subject ANOVA showed an effect of location ($F(1.86,35.4)=15.84$, $p<.001$), a trend for an effect of modality, ($F(1,19)=3.53$, $p=.076$) and an interaction between location and modality, ($F(2.19,41.75)$, $p<.001$). These results replicate the direction of the modality effect that we found in the Experiment 2 but only for the locations LR and RL. T-tests showed that the value of the BP at the visual LR was significantly smaller than the auditory LR, ($t(22)=-4.47$, $p<.001$) and the visual RL smaller than the auditory RL, ($t(21)=-3.6$, $p<.001$). Also, visual LL was significantly different than auditory LL, ($t(21)=2.3$, $p<.05$) but the direction of the effect was the opposite, with the participants overestimating the duration of the auditory stimuli. Furthermore, a within subject ANOVA was separately performed in each modality. The results showed an effect of location only in the visual modality, ($F(3,69)=.61$, $p<.05$). T-tests performed as post-hoc tests showed that visual LL was significantly different than visual RL, ($t(19)=4.1$, $p<.001$) as well as visual RR different than visual LR, $t((22)=4.76$, $p<.001$). These differences confirmed that participants overestimated the durations of the visual trials where the location of the second stimulus was different in comparison to the ones where the location was the same.

Table 3.3 also shows the Weber ratios. Weber ratios seem to vary dramatically between modalities. This modality effect was confirmed by a repeated measures ANOVA, ($F(1,19)=64.50$, $p<.001$). The location effect was not significant. This difference replicated the result that we got in the two previous experiments whereby participants had higher temporal sensitivity in the auditory modality. The values of the Weber ratios in this experiment are higher in both modalities than in the

two previous experiments. This finding shows that participants had lower temporal sensitivity in Experiment 3, possibly due to the higher cognitive demands of this task.

Table 3.3. Bisection points (BP) and Weber ratios (WR) from Experiment 3

	Condition	BP (mean)	WR (mean)
Visual	LR	268**	0.095
	RL	274**	0.095
	RR	315	0.109
	LL	328••	0.096
Auditory	LR	299	0.042
	RL	304	0.041
	RR	309	0.042
	LL	305	0.039

**p<0.01 significant overestimation, ••p<0.01 significant underestimation

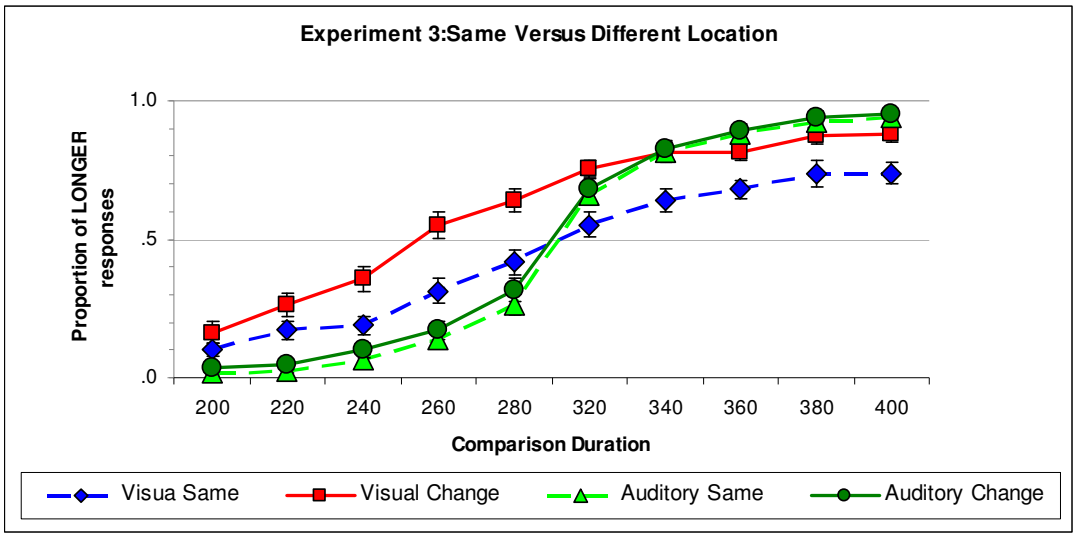


Figure 3.12. Psychophysical functions (mean proportion of LONGER responses plotted against comparison stimulus duration) from the auditory and visual conditions for combined *same location* conditions (RR –LL) and *change of location* conditions (LR –RL).

3.4.3 Interim Discussion of Experiment 3

In Experiment 3 the effect of modality on temporal sensitivity was replicated. Participants performed with higher precision in the auditory trials across all three experiments. Analysis of the bisection points and proportion of longer responses confirmed the expectations that Experiment 2 raised, namely that participants tend to overestimate visual trials but only when the location of the second stimulus was different than the first. In contrast, when the location was not changing participants tended to underestimate the visual trials. This effect supports the hypothesis that it is the monitoring of two different locations and shifting of spatial attention between them that gives rise to this overestimation of visual trials compared to auditory. Indeed, when participants didn't need to shift their attention between two different locations, an underestimation of visual trials was observed, consistent with the previously observed modality effect on subjective duration. It should be noted that the overestimation bias in participants' perceived duration of visual stimuli was not observed in Experiment 1, when visual and auditory trials were presented in separate blocks. However, it is not clear from the results presented thus far, whether this effect requires intermixed modality presentation. In Experiment 3, participants exhibited overestimation in the visual *change of location* trials in comparison to both auditory and visual *same location* trials. Thus, an additional experiment was conducted only in the visual modality; the procedure was identical to the one in Experiment 3 apart from the fact that there were no auditory trials.

This differential performance between *same location* and *change of location* trials in the visual modality is also manifested in the error and reaction time data (particularly when comparing the performance between shorter than 300 ms and

longer than 300 ms duration ranges). In the *same location* visual condition participants exhibited more similar reaction times between the two duration ranges, whereas in the *change of location* condition reaction times are much faster in the longer range. Furthermore, participants made more errors in the shorter duration range when the location changes while when the location is the same more errors are observed in the longer duration range.

Reaction times were slower overall for auditory trials than for visual, as in Experiment 2. Furthermore, reaction times for the longer range were faster than for the shorter for both modalities. Faster reaction times for longer than the standard stimuli have also been found in a previous study using a temporal categorization task (N'Diaye et al., 2004). This difference was explained in terms of differential processing of shorter and longer stimuli with longer stimuli been categorized as soon as the standard duration (300 ms) has elapsed.

A differential effect of right and left side of space was not observed in Experiment 3 either. Moreover, there was no effect of any of the spatial manipulations in the auditory domain. Although the change of the location affected visual trials, monaural presentation did not influence auditory temporal judgments, a finding that shall be discussed in the general discussion at the end of this chapter.

3.5 Experiment 4 – Introduction

Experiment 4 used the same four location conditions as Experiment 3. The only difference was that this experiment was conducted in the visual modality only. The aim of this experiment was to investigate the effect of location change (relative to no change of location) in the absence of auditory trials. The main question here is

whether the overestimation of the visual *change of location* trials will still occur despite the fact that participants are asked to make only visual judgements. This overestimation was attributed to spatial attention shifts. If shifting visual attention is a sufficient cause of this bias in visual temporal performance, then we would expect to observe it in the present experiment too. This experiment also further investigated how reaction times vary between *same location* and *change of location* trials.

3.5.1 Methods

A. Participants

Ten female and seven male students of the University of Edinburgh from 18 to 30 years in age (M = 23.58, SD = 3.2) participated in a single experimental session that lasted approximately 25 minutes. They were paid £4 for taking part in the experiment. All of them were right-handed and had normal hearing and normal or corrected-to-normal vision. The data of two participants were excluded from the analysis due to high level of inaccurate responses (they scored with more errors than 2 standard deviations above the mean error performance of the group). Therefore, data from 15 participants were analysed.

B. Apparatus and Stimuli

The apparatus was the same as in the previous experiments with the exemption that there were no auditory trials.

C. Procedure

The structure of the Experiment 4 was identical to the structure of the visual trials of Experiment 3 with four location conditions (RR – LL – LR – RL). As only the visual block of trials was presented there was no cue indicating the modality of the trials. Each participant performed 320 trials in total with a break in the middle of the session in order to rest.

3.5.2 Results

No differences between left and right side presentation (between LR & RL and between RR & LL) were found in any of the measures as in all previous experiments. Thus the results from the combined conditions LR & RL – referred to as change *of location condition* – and from RR & LL – referred to as *same location* condition – are presented here (as it was for Experiment 3).

A. Error percentages

The mean percentage of errors was 30%. A repeated measures ANOVA was conducted with location (same vs change) and duration of the comparison stimulus as factors. The ANOVA found a significant effect of duration, ($F(2.2,30.93)=12.35$, $p<.001$). Also the interaction between location and duration, ($F(3.58,50.15)=5$, $p<.01$) was significant. Inspection of the Figure 3.13 suggests that there is a difference in performance between shorter and longer duration ranges and this difference appears to be larger for the *same location* conditions (RR & LL). In order to further investigate this observation an additional ANOVA was conducted with the

same two factors: location (same versus change) and duration. Duration in this case though had two levels, shorter and longer. A main effect of duration, ($F(1,14)=9.73$, $p<.01$), was observed – indicating a higher percentage of errors in the longer range (38.5%) than in the shorter range (23.5%) – and a significant interaction between location and duration, ($F(1,14)=9.48$, $p<.01$). This interaction suggests that although in the *same location* condition participants made much more errors in the longer duration range (43%) compared to the shorter duration range (19.7%), in the change *of the location* condition their performance is more similar (27% for the shorter range versus 33% for the longer range). These observations were confirmed by t-tests conducted as post-hoc tests; the difference between shorter and longer range was found to be significant for the *same location* condition ($t(14)=-4.2$, $p<.001$) but not for the *change of location* condition.

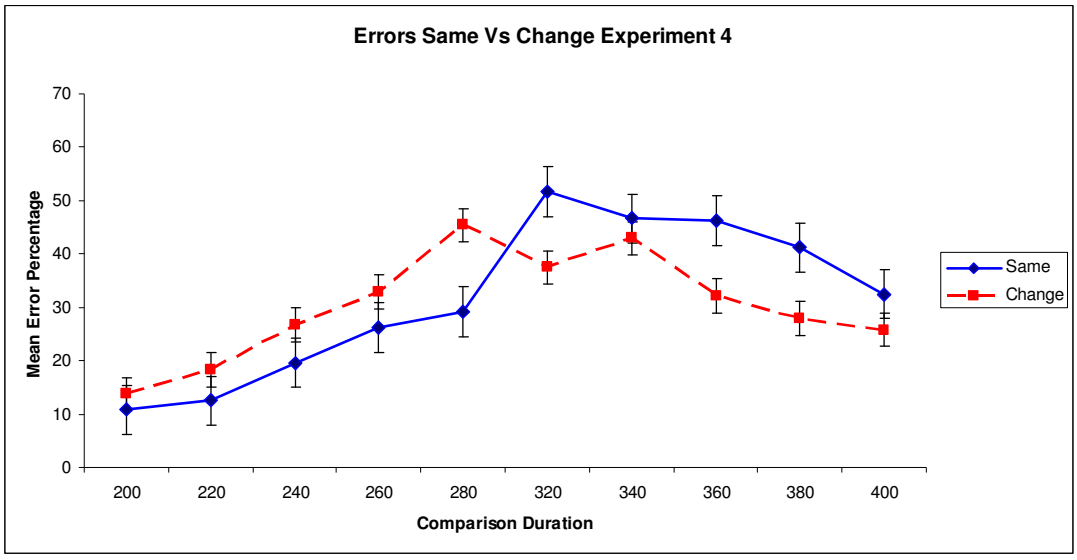


Figure 3.13. Mean Error percentages plotted against comparison stimulus duration from the visual trials and comparing the performance between *same location* conditions (RR – LL) and *change of location* (LR – RL) conditions.

B. Reaction times

The average reaction time was 616 ms. A repeated measures ANOVA with two factors (location and duration) revealed a trend for an effect of location, ($F(1,14)=3.8$, $p=.072$) and a significant effect of duration, ($F(3.9,55.9)=3.33$, $p<.05$). This trend for the effect of location suggested faster reaction times for the *same location* trials (600 ms) compared to the *change location* trials (631 ms). Inspection of Figure 3.14 suggests a small difference between shorter and longer duration ranges. In order to further investigate the effect of duration range, an ANOVA was conducted with the same two factors but with the difference that duration had two levels (shorter versus longer) instead of ten. In addition to the trend for the location effect, a trend for a duration effect was also observed, ($F(1,14)=3.13$, $p=.099$). This trend suggests slower reaction times for the longer (630 ms) than for the shorter range (602 ms). Although the interaction between location and duration was not significant the mean values of the different conditions suggest a different effect of duration range between *same location* and *change of location* conditions (for the *same location*, mean RTs were 573 ms for the shorter range and 627 ms for the longer range, whereas in the *change of location* condition participants' mean RTs were almost identical in the two ranges: 630 ms for shorter and 632 ms for longer). These differences were confirmed by t-tests conducted as post-hoc tests; only the t-test for the *same location* was significant, ($t(14)=2.13$, $p<.05$).

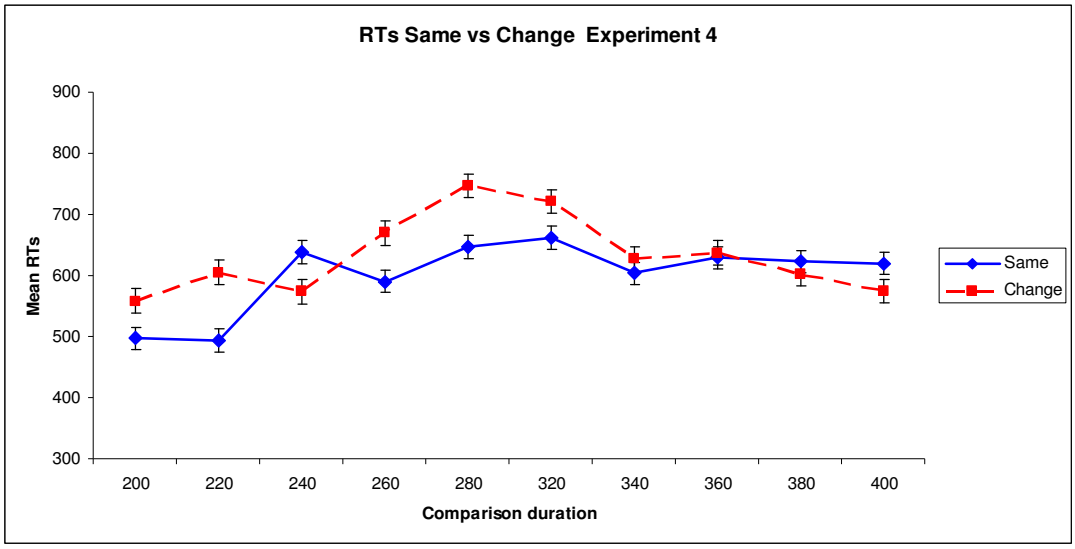


Figure 3.14. Mean Reaction times plotted against comparison stimulus duration from the visual trials comparing the performance between *same location* (RR – LL) and *change of location* (LR – RL) conditions.

C. Psychophysical functions

Figure 3.15 shows the psychophysical functions from the different location conditions with *same location* (RR & LL) trials being combined and *different location* (LR & RL) trials being combined – the combined presentation of the above location conditions is due to the fact that there was no significant difference between left and right locations, but only difference between *same location* and *change of location* conditions. A right displacement of the same location function is apparent. A repeated measures ANOVA was conducted with location and duration as factors and found significant main effects of both location, ($F(1,14)=8.9$, $p<.05$) and duration, ($F(2.9,42.9)=66.2$, $p<.001$). Participants in the *same location* conditions had significantly lower proportion of *longer* responses compared to the *change of location* conditions indicating an underestimation of the *same location* trials.

Bisection points and Weber ratios for Experiment 4 are shown in Table 3.4. The bisection points at RR and LL are displaced to the right of the arithmetic mean, indicating underestimation of temporal judgments, whereas LR and RL bisection points are close to the arithmetic mean, suggesting an absence of a systematic bias in these conditions. T-tests showed that LL was significantly different from both LR, ($t(14)=3.4$, $p<.001$) and RL, ($t(14)=2.9$, $p<.01$) and that RR was different than LR, ($t(14)=2.1$, $p<.01$). These differences confirmed that participants underestimated *same location* trials compared to *change of location* trials.

Table 3.4 indicates that the Weber ratios did not differ between conditions, an observation that was confirmed by subsequent analysis.

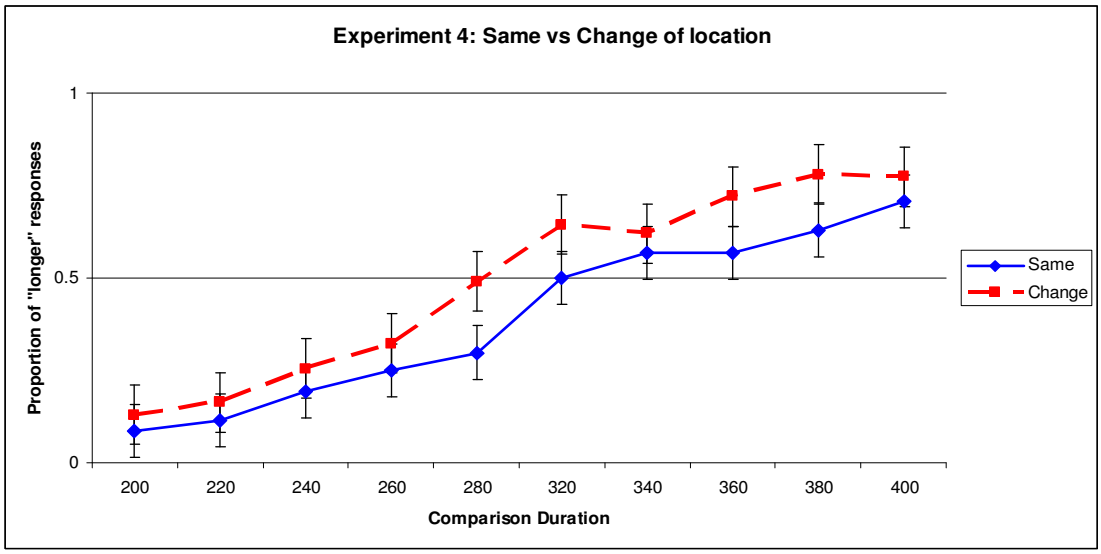


Figure 3.15. Psychophysical functions (mean proportion of LONGER responses plotted against comparison stimulus duration) for combined *same location* conditions (RR –LL) and *change of location* conditions (LR –RL).

Table 3.4. Bisection points (BP) and Weber ratios (WR) from Experiment 4

Condition	BP (mean)	WR (mean)
LR	304	0.095
RL	305	0.099
RR	333••	0.107
LL	353••	0.084

••p<0.01 significant underestimation

3.5.3 Interim Discussion of Experiment 4

Overestimation of *change of location* trials was not observed in Experiment 4. In contrast, a strong compression of the duration of the *same location* trials was observed. This underestimation of *same location* trials was also observed in Experiment 3, but in that case it had been attributed to the combined presentation of visual and auditory trials. However, it seems that the mixed modality presentation was not the only factor leading to this underestimation bias, as having just *same location* and *change of location* visual trials in one session appears to be enough in order for the effect to appear[5].

The fact that an absolute overestimation of *change of location* trials was not observed in this experiment indicates that spatial attention shifts are not the only factor underlying this effect. A combination of spatial attention shifts and mixed modality presentation is suggested to be required in order for the overestimation to take place.

[5] Having *same location* and *change of location* visual trials intermixed in the same session appears to be necessary though for the underestimation effect to appear. A previous experiment that we conducted (as part of a fourth year project) examined participants' performance in visual duration discrimination when *same location* and *change of location* trials were presented in separate blocks. The underestimation bias was not observed there.

The differential performance between *same location* and *change of location* trials was also manifested in the error and reaction time data. In the *same location* condition participants made many more errors in the longer than in the shorter duration range, whereas in the *change of location* condition the performance between the two duration ranges was quite similar. Also the reaction times between shorter and longer duration ranges were more similar in the *change of location* condition whereas participants seemed to be relatively faster in the shorter range than in the longer range in the *same location* condition.

Table 3.5. Mean Error and RT performance for shorter and longer duration ranges across all conditions for Experiments 1-4

Condition			Exp. 1		Exp. 2		Exp. 3		Exp. 4	
		Duration Range	Errors %	RTs (ms)	Errors %	RTs (ms)	Errors %	RTs (ms)	Errors %	RTs (ms)
Visual	Same	Shorter	-	-	-	-	22.0*	598	19.7**	573*
		Longer	-	-	-	-	30.6*	563	43.0**	627*
	Change	Shorter	24.9	545	29.0*	619**	36.2**	617*	27.3	630
		Longer	26.4	539	20.3*	555**	16.4**	497*	33.1	632
Auditory	Same	Shorter	-	-	-	-	10.3	723	-	-
		Longer	-	-	-	-	14.2	684	-	-
	Change	Shorter	17.0*	601*	10.7	710*	12.0	734	-	-
		Longer	11.2*	534*	10.7	663*	14.0	670	-	-

*p<.05 for difference between Shorter and Longer duration range conditions, **p<.01 for difference between Shorter and Longer duration range conditions

3. 6 General Discussion: Experiments 1- 4

Taken together, the results of Experiments 1 - 4 show clear modality and location effects. Firstly, in all four experiments participants were found to be significantly

more accurate and having higher temporal sensitivity (lower Weber ratios) in the auditory modality. This finding corroborates the results of previous studies suggesting the superiority of the auditory domain in duration judgments (see section 2.1.1). Participants' higher discrimination performance in the auditory modality was independent from the general cognitive demands of the task (mixed or blocked modality presentation and number of spatial locations). Furthermore, temporal sensitivity was not much affected by the differential demands of the task, as in all experiments participants' Weber ratios were quite similar (at least in the auditory trials). In the visual trials, the Weber ratios for Experiments 3 & 4 were slightly higher than for Experiments 1 & 2, suggesting that mixing *same location* and *change of location* conditions, and thus inducing uncertainty about the location of the second stimulus, makes visual temporal judgments more difficult.

3.6.1 Effects of location on perceived duration: overestimation of change of location

One of the central predictions that was made for the present experiments referred to the differential effects of right and left side of presentation in subjective duration. Contrary to the predictions for longer temporal judgments associated with the right space and shorter temporal judgments associate with the left space, no effect of location per se was observed in any of the experiments and any of the measures. This finding was surprising as the first experiment aimed to replicate Vicario et al.'s study (2008), using the same paradigm and stimuli and following the same procedure. Furthermore, the number of the participants in each of the present experiments was larger than at Vicario's study where eight participants were used.

Nevertheless, although an effect of position per se was not found, an effect of change of location was observed; participants tended to overestimate the duration of the comparison stimulus in visual trials in the *change of location* condition wherein the comparison stimulus appeared in a different location from the preceding standard stimulus. This overestimation of *change of location* visual trials (which is reflected on the higher proportion of actual *longer* responses of participants in these conditions) was firstly observed in Experiment 2. Previous studies have provided evidence for overestimation of auditory temporal judgments where they are intermixed with visual judgments in the same session (see section 2.1.2.*C*). However, in the present experiments the opposite effect was observed.

It is worth noting that previous studies investigating modality differences in duration perception involved central presentation of visual stimuli and binaural presentation of sounds. In the four experiments presented in this chapter, the visual stimuli were presented in two different spatial locations. Therefore, participants had to monitor two different locations and shift their attention between them. Shifts of spatial attention, both sustained and transient, have been found to affect the subjective duration in previous studies (see section 2.3.2). Manipulation of spatial attention (mainly via attentional cues) seems to increase the subjective duration of brief stimuli. Although, participants' spatial attention was not directly manipulated via a cue, monitoring the change of the location on the left and on the right while fixating on the centre requires transient shifts of spatial attention between the two positions. Indeed, change of location of visual stimuli has been found to affect perceived duration in a dual task experiment (Cicchini & Morrone, 2009; see section

2.3.2.*A*). A compression of duration was observed in this experiment for an empty interval marked by bars presented in separate locations. In this experiment, participants were instructed to keep central fixation throughout the trial, without the fixation being controlled, as in our experiments. When the interval was marked by bars in the same location no distortion of duration was observed. The effect that was observed by Cicchini & Morrone (2009) seems to be quite different than the effect that was observed in the present experiments.

However, it should be noted that the procedure in Cicchini & Morrone (2009) study was quite different. The intervals to be judged were empty unlike in the present experiments which only involved the presentation of filled intervals. Furthermore, a second concurrent visual non-temporal task was performed by the participants. Despite the differences in the design both studies suggest that change of the location plays an important role in the subjective perception of duration. Thus, the results of Experiment 2 were attributed to the location change and the allocation of spatial attention. In order to test this hypothesis Experiment 3 was conducted that involved both *change of location* and *same location* conditions. The results of this experiment confirmed the hypothesis that spatial attention shifts were underlying participants' longer duration judgments. Participants were found again to overestimate visual trials but only in case that the location of stimuli was changing. When the stimuli were appearing on the *same location*, then the opposite effect was observed (underestimation of visual stimuli). This effect is consistent with the previously reported result on visual – auditory perceived duration differences.

Moreover, the overestimation effect in Experiment 3 was larger than the one in Experiment 2. In Experiment 2 participants' average overestimation was 15 ms

whereas in Experiment 3 it was around 30 ms. The difference between these two experiments was not only the number of possible location conditions but also the uncertainty about the location of the second stimulus. Whereas in Experiment 2 participants knew that the second stimulus is always going to appear on the opposite location than the first, in Experiment 3 the second stimulus could either appear on the same or the opposite location. This uncertainty about the location made Experiment 3 more attentional demanding than Experiment 2 which led to a greater overestimation effect.

It should be pointed out that the overestimation of visual trials in the *change of location* condition was observed only when visual and auditory trials were intermixed. When visual and auditory trials were presented in separate blocks (Experiments 1 & 4), no overestimation of *change of location* visual trials was found – regardless of the number of locations. Switching between the two modalities seems to result in differences in temporal processing.

In order to explain this overestimation of visual stimuli in the change of location condition, we propose that there is an error-correction mechanism at work, which manifests differently under different conditions. The role of this mechanism is to compensate for a loss of time, which results from spatial shifts of attention. Thus we hypothesize that when spatial attention is shifted from one location to another, this causes some loss of time; in terms of a clock model, this would be due to pulses being lost or forgotten during the spatial attention shift. In order to compensate for this loss of time, a certain duration is added to the estimation. This error-correction mechanism is similar to the compensation mechanism proposed by Yarrow et al. (2001), which specifically corrects for time lost during saccades. In the case of the

saccadic effect, an overestimation of the duration of visual stimuli following saccades is observed (referred to as chronostasis) (see Chapter 2, section 2.2.4). Both compensation mechanisms facilitate the relatively accurate duration discrimination. However unlike the saccadic mechanism which results in an apparent bias whenever a saccade is involved, the error-correction mechanism proposed here works seamlessly under most circumstances (i.e. when only visual trials are presented in the session). However, when visual and auditory trials are intermixed (as in Experiments 2 & 3), then it seems that the error-correction mechanism is overactivated (adding a larger duration than needed) leading to the apparent overestimation bias.

Furthermore, the overestimation bias is more prominent in Experiment 3 than in Experiment 2 suggesting that the cognitive load of the experiment is also affecting this mechanism. Cognitive load has been found to affect temporal performance with duration judgments (Block, Hancock & Zakay, 2010). In some previous studies it has also been observed that a concurrent task can mediate the effect of spatial attention on subjective duration of brief stimuli. The distortion of duration in Cicchini et Morrone's (2009) study took place when the attention was divided between the temporal task and another non-temporal task. In this case, there were both shifts of attention between the two tasks and spatial shifts of attention between the two targets. However, in the case of the present experiments, although a dual task paradigm was not involved, participants were required to alternate between different modality trials and shift their attention accordingly.

Hence, two alternative hypotheses could be formed. Firstly, it could be that it is not specifically the mixing of two modalities that leads to the overestimation effect but rather a more general effect of the higher attentional demands of this paradigm

where participants have to switch their attention between different modalities (similar to a divided attention paradigm). This hypothesis would be supported by the observation of this effect increasing when there are more location conditions (as in Experiment 3), and therefore higher demands on attentional resource.

On the other hand, it could be that the overestimation bias takes place as a result of specifically mixing the two modalities in a single session. Recent theories have suggested the existence of localized, modality specific temporal mechanisms (Karmakar & Buonomano, 2007). However, if there are separate modality mechanisms, then this would seem to imply the involvement of some mechanism for integrating the contributions of the modality specific mechanisms. When different modalities are presented in the same session then this mechanism is automatically activated, and the output of the different modalities is combined even if this is not required by the task. So apart from having to deal with the spatial attention shifts between the different locations where the visual stimuli are appearing, a combination/comparison of the output of the visual and auditory "clocks" needs to also take place. This could lead to a potential overcompensation (the brain thinks that more time was lost than actually was as it struggles to deal with the output of the different temporal mechanisms) and the present overestimation bias.

This overcompensation could result from the differences in speed between the visual and auditory "clocks" (see Chapter 2, section 2.1.2). It has been suggested that when visual and auditory trials are presented within the same session, a common standard is formed in the memory (dominated by the auditory standard) and this results in underestimation of visual trials (Penney, Gibbon & Meck, 2000). The overcompensation that was described above could thus be a result of the implicit

assumption that the auditory clock runs faster, according to which it is assumed that even more time needs to be added in the visual change of location trials. In other words, interference from the auditory domain causes the temporal error in the visual domain to be overestimated, and so overcorrected for.

In order to test these hypotheses, an additional experiment – which is presented in Chapter 5 – was conducted. In this experiment instead of intermixing visual temporal judgments with auditory judgments, visual temporal judgments were mixed with visual size judgments. If the first hypothesis concerning an effect of general cognitive load is more accurate then, a similar effect as in Experiments 2 and 3 would be expected. Otherwise, if the performance turns out differently, then the effect of modality mixing would be supported.

3.6.2 Effects of location on perceived duration: underestimation of the same location

An underestimation of the same location trials was observed in Experiments 3 and 4. This underestimation of visual temporal judgments when the location of the two stimuli remained the same was attributed to the previously reported visual – auditory differences in perceived duration. However, in Experiment 4, which was conducted only in the visual modality (involving *same location* and *change of location* trials), although the overestimation of *change of location* trials was not observed, the underestimation of *same location* trials was not only replicated but it appeared to be even greater than in Experiment 3. Thus, it seems to be independent of the modality mixing but dependent on the mixing of different location conditions as it appears when *change of location* and *same location* visual trials are intermixed in the same

session. It could be the case that compared to the *change of location* trials, the *same location* trials attract less attention and therefore lead to underestimations.

Underestimation of duration of stimuli that appear on the same location as the standard has previously been reported in local adaptation experiments (Johnston, Arnold & Nishida, 2006; see section 2.2.3). In the case of the adaptation to drifting motion or to flickering, comparison stimuli that were presented on the adapted spatial location, their duration were reduced. However, in the present experiments the short duration of the presentation of the standard stimulus (300 ms) makes this interpretation of the data unlikely. The underestimation of visual trials is further investigated in the following chapter.

3.6.3 Participants' reaction times

A. Differences between shorter – longer ranges

The difference in participants' performance between visual conditions where the stimuli appeared in the same location and conditions where the stimuli were changing location was also reflected in the reaction times.

In the *change of location* trials visual temporal judgments are much faster in the longer duration range (over 300) than in the shorter (but this difference is observed only when visual temporal judgments are intermixed with auditory temporal judgments within the same session: Experiments 2 and 3). This difference in reaction time performance in shorter and longer ranges occurs also for the auditory temporal judgments. A potential interpretation for faster judgments in the longer range could be that participants make their decisions during the comparison duration,

and as soon as the timed duration exceeds the duration of the standard stimulus they categorize the duration as *longer*.

An interesting finding is that the difference between shorter and longer ranges for the visual change of location trials is around 64 ms in Experiment 2 and becomes even larger (120 ms) in Experiment 3. In both experiments, visual reaction times are dropping considerably in the longer range whereas this difference between duration ranges remains almost the same for the auditory judgments across experiments.

This considerable reduction of visual reaction times in the longer range for the mixed modality presentation experiments appears to be consistent with the mechanism that was described above – adding of a specific duration on *change of location* trials. If a certain duration is being added (15 ms for Experiment 2 and 30 for Experiment 3) to the 280 duration the resulting duration is very close to the standard 300 ms and this could lead to slower reaction times. However, if this duration is added to the longer than 300 ms durations then these stimuli' duration becomes substantially larger than the standard, which could explain the drop in reaction times.

When visual stimuli appear on the same location, the pattern of reaction time performance is similar to the auditory pattern in Experiment 3. However, in Experiment 4 the opposite pattern is observed. Participants are slower in their judgments in the longer range when the location does not change. These slower reaction times accompany the greater quantity of errors in the longer range.

B. Modality effect on reaction times

Whereas in Experiment 1, where different modality trials were blocked, participants' reaction times were similar between visual and auditory domain, in Experiments 2 & 3 participants were found to have slower reaction times for the auditory domain than for the visual one. This finding seems inconsistent with a previous study where a temporal generalization task was used (N'Diaye et al., 2004) and participants were faster – as well as more accurate – in the auditory than in the visual domain. This finding was attributed to the better efficiency of the auditory modality for temporal processing. No previous studies measuring the differences in reaction times between modalities on duration discrimination were found. Thus it is difficult to interpret the present results across all conditions. However, this difference is more prominent in the longer range which can be attributed to the mechanism of duration addition that takes place only for the visual modality. There is still a smaller difference in reaction times for the shorter range which could be attributed to the fact that visual sensory memory last less (around 500 ms) than the auditory sensory memory (4 seconds). In this case, as the visual temporal judgments are also more difficult than the auditory, participants might give up and respond quicker as they do not really have the chance to improve their performance. In contrast, in the auditory domain they can take more time and make better judgments, thus their reaction times are slower compared to the visual.

3.7 Summary

Chapter 3 presented four experiments investigating the effects of right and left spatial presentation. Although an effect of location per se (right versus left) was not shown, effects of change of location – specific to the visual modality – were demonstrated. Specifically, overestimation of *change of location* conditions and underestimation of *same location* conditions were observed. As clear conclusions about the mechanism (or more probably the different mechanisms) underlying these effects cannot be drawn from the above experiments, additional experiments were conducted to clarify the core processes. These experiments are presented in the following chapters.

Chapter 4 –

THE EFFECTS OF VERTICAL (TOP VS BOTTOM) SPATIAL PRESENTATION ON VISUAL AND AUDITORY DURATION JUDGMENTS

In this Chapter, two experiments investigating the effects of top and bottom side presentation of visual stimuli on brief duration judgments are presented. In Chapter 3, no effect of location per se (right vs left) was found in any of the experiments. However, an overestimation the duration of *change of location* trials and an underestimation of the duration of *same location* trials was observed. The main aim of the present experiments was to clarify whether these findings were somehow related to the right and left side presentation of the stimuli. Thus, the central question is: does top and bottom presentation of stimuli produce the same or different effects as left and right presentation of stimuli?

4.1 Experiment 5 – Introduction

Experiment 5 investigated the effect of top and bottom presentation of visual stimuli on visual and auditory duration discrimination using two location conditions:

1) the standard stimulus appeared on the top side of the screen whereas the comparison stimulus appeared on the bottom of the screen (**TB** condition)
2) the standard stimulus appeared on the bottom of the screen and the comparison stimulus appeared on the top of the screen (**BT** condition).

As the effect of *change of location* and *same location* of stimuli presentation was found only when modality trials were mixed within the same session, mixed modality presentation was used in the present experiment. Experiment 5 had the same structure as Experiment 2 except for that the visual stimuli (circles) appeared at the top and bottom of the screen instead of the left and right side.

An additional change that was made to the experimental procedure of Experiment 5 regarded auditory stimuli presentation; instead of having right and left monaural presentation of sounds, there was only one auditory condition involving binaural presentation of sounds. The location of presentation did not affect auditory duration judgments in any of the measures in any of the experiments that were presented in the previous chapter. A second aim of the present experiment was to test if the effects that were found in the visual modality could be observed simply by mixing the visual trials with auditory duration judgments with no manipulation of the ear to which sounds were presented.

4.1.1 Methods

A. Participants

Eleven female and ten male students of the University of Edinburgh from 19 to 28 years in age (M = 23.6, SD = 3.1) participated in a single experimental session that lasted approximately 30 minutes. They were paid £5 for taking part in the experiment. All of them were right-handed and had normal hearing and normal or corrected-to-normal vision. The data of 2 participants were excluded from the analysis due to high level of inaccurate responses (their error performance was 2

standard deviations higher than the average of the sample). Therefore, data from 19 participants were analysed.

B. Apparatus and stimuli

The apparatus was the same as in the previous experiments except for the visual stimuli (circles) that were presented at the top or the bottom of the screen (8° eccentricity) on a white background. The auditory stimuli were presented binaurally via headphones at an intensity of 75 dB SPL.

C. Procedure

The structure of Experiment 5 was almost identical to the structure of Experiment 2 (see Chapter 3, section 2.1.2.*C*). Only the location, at which the visual stimuli were presented, was different; the standard stimulus could be either on the top or on the bottom of the screen and the comparison was in half of trials on the same side of the screen of the presentation of the standard stimulus and in the other half on the opposite side. Participants each performed 320 trials in total (160 visual trials and 160 auditory trials, randomly intermixed).

4.1.2 Results

As no significant differences were found in the error percentages and mean reaction times between TB and BT visual location conditions, the average data from these two conditions are used and presented here.

A. Error percentages

The percentages of errors were calculated for each experimental condition. Participants performed with 32% errors in the visual trials and 13% errors in the auditory trials. A repeated measures ANOVA was conducted with modality and duration of the comparison stimulus as factors. The ANOVA found both significant effects of modality, ($F(1,18)=234.8$, $p<.001$) and duration, ($F(2.9,52.8)=22.9$, $p<.001$). Also the interaction between modality and duration was significant, ($F(2.56, 52.8)=7.3$, $p<.001$). Inspection of the Figure 4.1 suggests that participants in the visual modality make many more errors when the duration of the comparison stimulus is less than the standard (300 ms) than when it is larger. In contrast, the auditory performance looks more similar between the two duration ranges. In order to further investigate this effect of duration between shorter and longer duration ranges, another ANOVA was conducted again with modality and duration as independent measures. However in this analysis the duration had 2 instead of 12 levels (shorter than 300 and longer than 300 durations). Apart from the modality effect, the ANOVA showed a significant effect of duration, ($F(1,18)=8.5$, $p<.01$) suggesting that participants made significantly fewer errors when the comparison duration was longer than the standard (18.5%) than when it was shorter (27%). There was also a significant interaction between duration and modality, ($F(1,18)=10.7$, $p<.01$) suggesting a difference between the duration ranges which occurred only for the visual trials. T-tests confirmed this observation with only the t-test comparing the shorter and longer range in the visual modality yielding significance, ($t(18)=3.4$, $p<.01$)(see Table 4.3 for mean error percentages across the different conditions). In

the auditory domain, performance was similar between shorter and longer duration ranges.

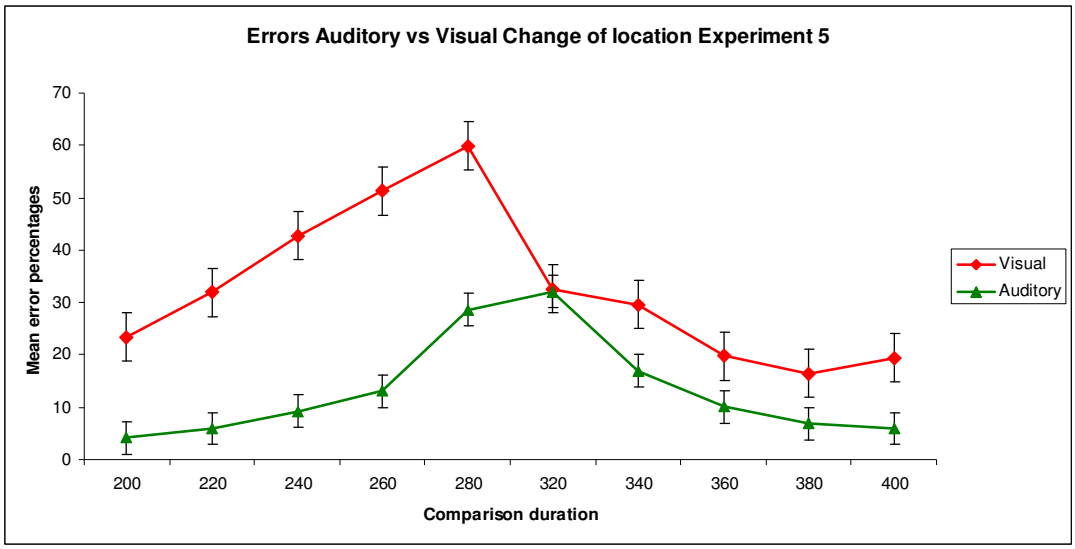


Figure 4.1. Mean Error percentages from the auditory and visual conditions of Experiment 5

B. Reaction times

Mean reaction times were 743 ms for the visual trials and 855 ms for the auditory trials. It seems that in Experiment 5, as in Experiments 2 and 3, participants were slower in auditory modality than in the visual. Indeed, this observation was confirmed by the analysis. A repeated measures ANOVA with two factors (modality and duration) revealed a significant effect of modality, ($F(1,18)=12.2$, $p<.001$) and of duration, ($F(3.3, 60.4)=9.7$, $p<.001$) and a significant interaction between modality and duration, ($F(4.8,87)=5.8$, $p<.001$). In order to further investigate the effect of duration we conducted another ANOVA with shorter and longer than the standard stimulus durations. A trend for a significant effect of duration was found, ($F(1,18)=3.4$, $p=.080$) with participants being slower when the comparison stimulus

is shorter than the standard (828 ms) compared to when it is longer (770 ms). Although the interaction between modality and duration was not significant inspection of Figure 4.2 of the mean values for each condition (see Table 4.3) suggests that although there is not much difference in RTs between shorter (846 ms) and longer (865 ms) duration ranges for auditory stimuli, there was a tendency for a difference in performance between shorter (791 ms) and longer (695 ms) durations for visual stimuli.

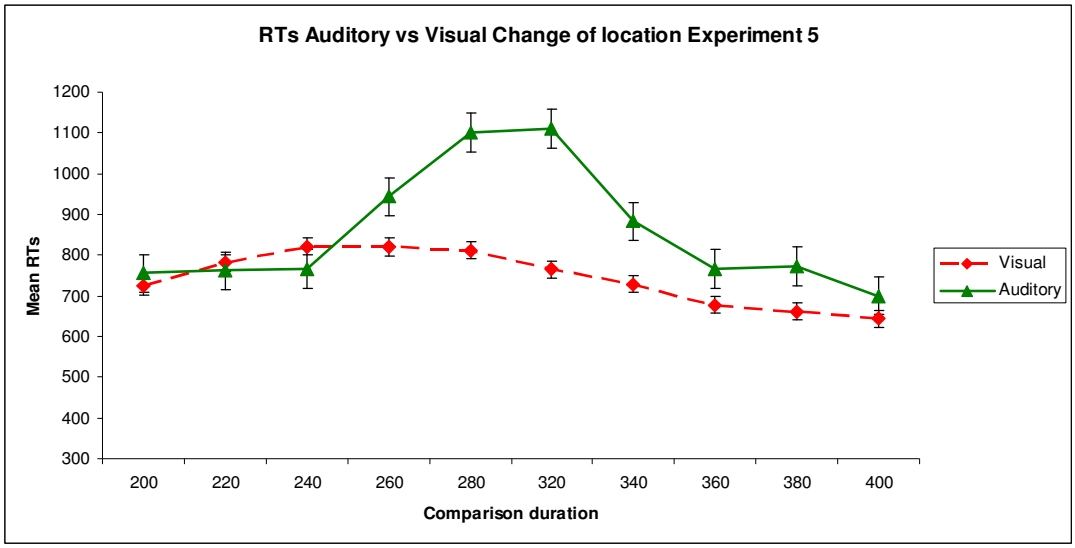


Figure 4.2. Mean reaction times from the auditory and visual conditions of Experiment 5

C. Psychophysical functions

Figure 4.3 shows the psychophysical functions in the visual and auditory trials. Inspection of this figure suggests that the proportion of *longer* responses increases with the comparison stimulus duration and also that the slope for the visual condition is flatter than the auditory one. A repeated measures ANOVA was conducted with two factors (modality, duration). The ANOVA found effects of modality,

($F(1,18)=10.16$, $p<.01$) and stimulus duration, ($F(2.6, 46.9)=227.9$, $p<.001$). There was found higher proportion of *longer* responses in the visual trials compared to the auditory. Also the interaction between modality and duration was found to be significant, ($F(9,162)=45.4$, $p<.001$).

In order to further investigate the differences between the psychophysical functions in the different conditions, the individual bisection points and Weber ratios were calculated from the psychophysical functions. The resulting bisection points for the different experimental conditions are shown in Table 4.1. Inspection of the values in Table 1 points out a difference between modalities with the visual bisection points having smaller values than the auditory. This difference suggests an overestimation of the visual durations compared to the auditory one. T-tests revealed that the auditory BP was significantly higher than both visual TB, ($t(18)=-2.3$, $p<.01$) and visual BT, ($t(18)=-4.7$, $p<.001$). This difference shows that participants were overestimating the comparison duration of the visual trials. Also, the BP for visual TB was significantly higher than for visual BT, ($t(18)=2.36$, $P<.05$), suggesting larger overestimation biases in the BT condition.

The Weber ratio values are also shown in Table 4.1. As in the previous experiments, inspection of the values shows that the Weber ratios between modalities are very different. This effect was confirmed by t-tests. Both TB and BT visual conditions were found to have higher WR values than the auditory conditions, ($t(18)=5.1$. $p<.001$) and ($t(18)=5.7$, $p<.001$) respectively. Therefore, participants had higher temporal sensitivity in the auditory modality.

Table 4.1. Bisection points (BP) and Weber ratios (WR) from Experiment 5

Condition	BP (mean)	WR (mean)
Visual TB	282*	0.087
Visual BT	263**	0.093
Auditory	300	0.036

*p<0.05 significant overestimation, **p<0.01 significant overestimation

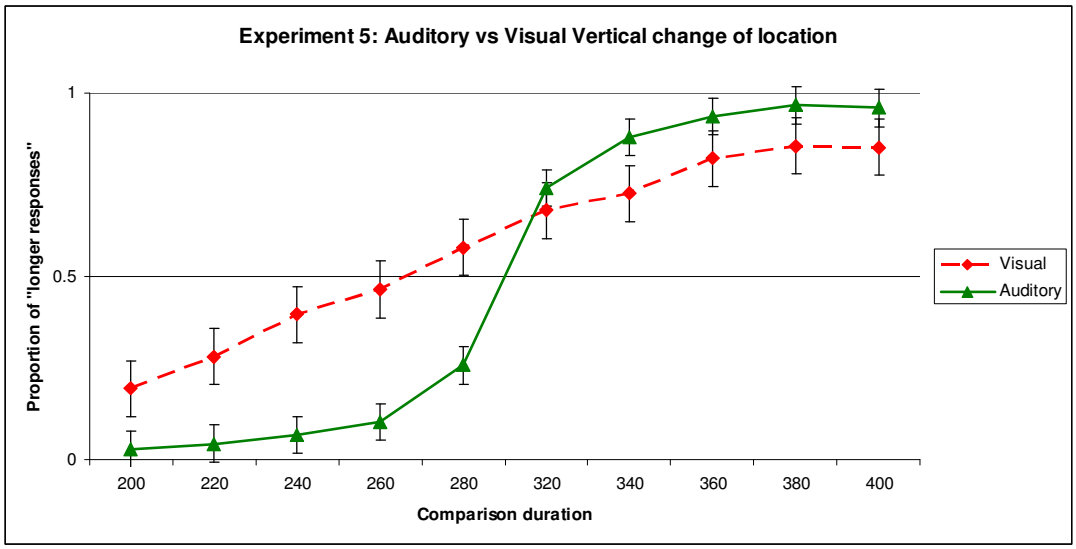


Figure 4.3. Psychophysical functions from the auditory and visual condition of Experiment 5. A leftward displacement of the visual functions on the 0.5 point indicates participants' overestimation of visual trials

4.1.3 Interim Discussion of Experiment 5

Experiment 5 replicated the effects that were observed in the Experiment 2 as described in the previous chapter. Participants gave a higher proportion of longer responses in the visual modality than in the auditory. Therefore, it seems that it is indeed the change of the location, irrespective of the side of presentation (horizontal or vertical), which leads to the overestimation of visual temporal judgments. The only differential effect between top and bottom visual presentation appeared on the bisection points with BT visual presentation yielding lower BP values than TB visual

presentation, a result that indicates greater overestimation in this location condition. Despite the fact that there is a difference in bisection points, still the bias is towards the same direction; in both cases, participants tended to overestimate the visual stimuli and not to have biased discrimination of the auditory stimuli.

Furthermore, reaction time performance was similar to Experiment 2. Reaction times were shorter in the visual modality than the auditory; visual reaction times were also slower in the longer duration range compared to the shorter duration range.

The fact that auditory stimuli were presented binaurally instead of monaurally did not seem to lead in a differential pattern of performance. The overestimation of visual trials still appeared, despite the fact that there was no manipulation of the side of sound presentation.

In this experiment, only *change of location* visual trials were used. Hence, another experiment with the addition of visual *same location* conditions was conducted.

4.2 Experiment 6 – Introduction

Experiment 6 was similar to the previous experiment with the only difference being the number of the location conditions. Instead of having just two *same location* conditions, four location conditions were used in the present experiment, two *change of location* (TB, BT) and two *same location* (TT, BB). Therefore, when the standard stimulus appeared at the top of the screen, the comparison could appear either at the top or bottom of the screen, and when the standard was presented at the bottom of the screen, the comparison could appear at either the bottom or the top of the screen.

As the side of the presentation of the sounds was not found to affect participants' performance in any of experiments of the previous chapter though mixed modality presentation still yielded the overestimation effect of the *change of location* conditions, tones were again presented binaurally as in Experiment 5.

The main question here regarded the overestimation of the change of location trials; is the effect going to be stronger than in Experiment 5 considering that the combination of locations is more diverse (similarly to the Experiment 3)? Or will there by an underestimation of the same location visual trials (TT and BB) as in Experiments 3 and 4?

4.2.1 Methods

A. Participants

Twelve female and nine male students of the University of Edinburgh from 18 to 29 years in age (M = 23.6, SD = 3.5) participated in a single experimental session that lasted approximately 50 minutes. They were paid £7 for taking part in the experiment. All of them were right-handed and had normal hearing and normal or corrected-to-normal vision. The data of two participants were excluded from the analysis due to high level of inaccurate responses (their error performance was 2 standard deviations higher than the average of the sample). Therefore, data from 19 participants were analysed.

B. Apparatus and Stimuli

The apparatus was the same as in the previous experiment. The procedure differed during the stage of the presentation of the variable comparison stimulus. The comparison stimulus was presented in half of the trials on the same side of the screen of the presentation of the standard stimulus and in the other half on the opposite side of the presentation of the standard stimulus. This resulted in having four levels of spatial position for each modality, Top – Top (TT), Bottom - Bottom (BB), Top – Bottom (TB) and Bottom –Top (BT).

C. Procedure

The structure of the Experiment 6 was identical to the structure of the Experiment 3 (in Chapter 3). The only differences being that instead of having horizontal presentation (left versus right) the presentation of the visual stimuli was vertical and there was just one condition for the auditory modality with binaural presentation of stimuli. Participants each performed 640 trials in total (320 visual trials and 320 auditory trials intermixed).

4.2.2 Results

The error and reaction time analysis did not show any differences between the location conditions TB & BT and between the location conditions TT & BB. Thus, TB & BT data are combined and referred to as *change of location* condition and the TT & BB data are combined and referred to as *same location* condition. The results from these combined location conditions are presented below.

A. Error percentages

Participants performed with 31.5% errors in the visual trials and 11% in the auditory trials. A repeated measures ANOVA was conducted with modality, location (same vs change) and duration of the comparison stimulus as factors. The ANOVA found a significant effect of modality, ($F(1,18)=185.2$, $p<.001$) and duration, ($F(1.9,35.5)=31$, $p<.001$). Also the interaction between location and duration, ($F(3.4,61.6)=12.2$, $p<.001$) was significant. Inspection of Figure 4.4 suggests that there was a difference in performance between shorter and longer duration ranges in the visual *change of location* condition whereas there was less difference between the shorter and longer ranges in visual *same location* and auditory condition.

In order to further investigate this observation an additional ANOVA was conducted for the visual trials with two factors: location (same versus change) and duration with two levels (shorter versus longer). Although neither main effect was found to be significant, the interaction between location and duration was significant, ($F(1,18)=24.7$, $p<.001$). This interaction indicates that although in *change of location* participants made more errors in the shorter range (40.7%) compared to the longer range (22.7%), in the *same location* condition the opposite pattern was observed (although the effect looks smaller) with participants committing more errors in the longer range (38.1%) than in the shorter range (24.6%). These differences were tested with t-tests revealing a significant difference between duration ranges in the change of location, ($t(18)=2.97$, $p<.001$) whereas there was a trend for a significant effect in the same location, ($t(18)=-2.1$, $p=.051$). The differences in performance of

participants between longer and shorter range in the auditory modality were not significant.

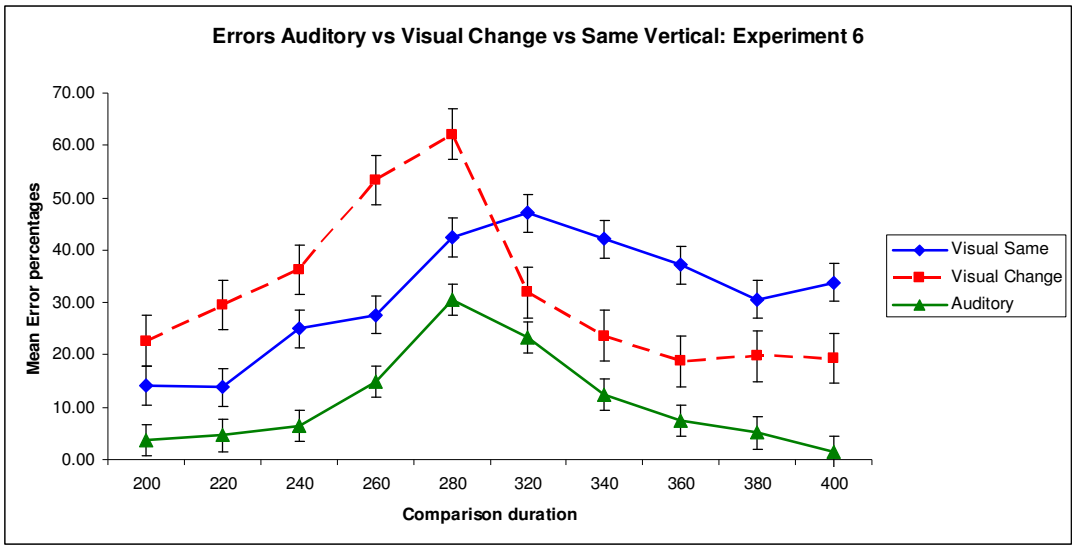


Figure 4.4. Mean Error percentages plotted against comparison stimulus duration from visual and auditory trials and comparing the performance between visual *same location* (TT – BB) and **change of location** (TB – BT) conditions.

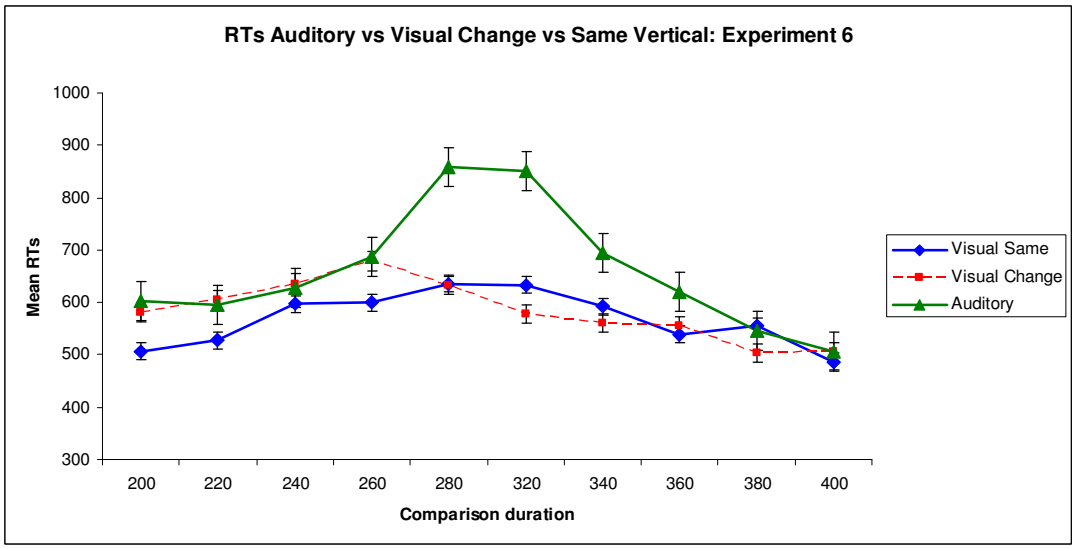


Figure 4.5. Mean Reaction times plotted against comparison stimulus duration from visual and auditory trials and comparing the performance between visual *same location* (TT – BB) and *change of location* (TB – BT) conditions.

B. Reaction times

Participants' average reaction times in this experiment were 575 ms for the visual trials and 658 ms for the auditory trials. Similarly to the previous experiments participants' reaction times appear to be faster for visual than for auditory trials. This observation was confirmed by the analysis. A repeated measures ANOVA with three factors (modality, location and duration) was conducted. Significant effects of modality, ($F(1,18)=17.1$, $p<.001$) and of duration, ($F(3.5,63.9)=13.3$, $p<.001$) were found. Also, a significant interaction between modality and duration, ($F(4.5,81.1)=6.3$, $p<.05$) was observed. Figure 4.5 shows a larger difference in reaction times between shorter and longer duration ranges for the visual *change of location* condition. This difference between duration ranges seems to be smaller for visual *same location* and auditory condition.

In order to further investigate these effects of duration, an additional ANOVA was conducted for the visual modality with two factors: location (same versus change) and duration with two levels (shorter versus longer). Duration was found to have a marginally significant effect, ($F(1,18)=4.1$, $p=.057$), with participants being significantly faster in the longer range (550 ms) than in the shorter range (600 ms). A significant interaction between location and duration, ($F(1,18)=5.1$, $p<.05$) was also observed. This interaction indicates a significantly larger difference between shorter and longer ranges for the *change of location* condition (626 ms vs 540 ms respectively) than for the *same location* condition (573 ms vs 561 ms respectively). A t-test on the change of location condition revealed significance, ($t(18)=2.6$, $p<.01$) whereas no significant differences between shorter and longer ranges were found for the *same location* condition. The difference between shorter and longer ranges was

not found to be significant for the auditory RTs (674 ms for shorter versus 642 ms for longer) (see also Table 4.3 for mean RT values across the different conditions).

C. Psychophysical functions

Figure 4.6 shows the psychophysical functions in the visual and auditory trials, indicating a leftward displacement of the visual change of location trials (suggesting overestimation) and a rightward displacement of the visual same location trials (suggesting underestimation). A repeated measures ANOVA was conducted with modality, location (2 levels: same versus change of location) and duration as factors. The ANOVA found main effects of location, ($F(1,18)=26.8$, $p<.001$) and duration, ($F(2.4,44.2)=427.7$, $p<.001$). Also the interactions between modality and location, ($F(1,18))=26.8$, $p<.001$), modality and duration, ($F(4.2,75.7)=46.8$, $p<.001$) and location and duration, ($F(9,162)=2.1$, $p<.05$) were significant. It seems that participants gave a higher proportion of *longer* responses in *change of location* trials compared to same *location trials*. An ANOVA was conducted only on the visual modality with two factors, location and duration. Both location, ($F(1,18)=26.8$, $p<.001$) and duration, ($F(3.3,60)=82$, $p<.001$) as well as their interaction, ($F(9,162)=2.1$, $p<.05$) were found to be significant. Participants gave a higher proportion of *longer* responses in the *change of location* trials whereas they gave a lower proportion of *longer* responses in the *same location trials*. Two additional ANOVAs were conducted separately on the *same location* and on the *change of location* conditions in order to test the modality effect, with two factors, modality and duration. In both cases, the modality effect was found to be significant: for the *same location*, ($F(1,18)=5.7$, $p<.05$) and for the *change of location*, ($F(1,18)=5.1$, $p<.05$),

although the direction of the effect was the not the same; in the *same location* condition participants gave a lower proportion of *longer* responses in the visual trials compared to the auditory, whereas they gave a higher proportion of *longer* responses at the visual *change of location* trials compared to the auditory ones.

Bisection points and Weber ratios for Experiment 6 are shown in Table 4.2. The BP values look similar to the ones of Experiment 3 (Chapter 3), with the visual bisection points from the *same location* conditions being similar between them and larger than the auditory (suggesting overestimation) with the opposite pattern for the *change of location* visual bisection points. The within subject ANOVA showed an effect of location ($F(3,57)=12.53$, $p<.001$) and an interaction between location and modality, ($F(3,57)=12.53$, $p<.001$). T-tests showed that the value of the BP at the visual TT was significantly larger than the auditory, ($t(18)=2.55$, $p<.05$) and the visual BB larger than the auditory, ($t(18)=3.1$, $p<.01$). Also, visual BT was significantly different than auditory, ($t(18)=-2.51$, $p<.05$) but the direction of the effect was the opposite, with the participants overestimating the duration of the visual stimuli. T-tests also showed that visual TT was significantly different than visual TB, ($t(18)=4.26$, $p<.001$) as well as visual BB different than visual BT, ($t(18)=3.7$, $p<.001$). Figure 4.7 illustrates the differences between visual and auditory bisection points in Experiment 6.

Weber ratios between modalities are again different. This modality effect was confirmed by a within-subjects ANOVA, ($F(1,18)=102.3$, $p<.001$). The location effect was not significant. This difference is consistent with all previous experiments where participants exhibited higher temporal sensitivity in the auditory modality.

Table 4.2. Bisection points (BP) and Weber ratios (WR) from Experiment 6

Condition	BP (mean)	WR (mean)
TB	278*	0.100
BT	277*	0.093
TT	331••	0.098
BB	323•	0.079
Auditory	297	0.032

*p<0.05 significant overestimation, •p<0.05 significant underestimation, ••p<0.01 significant underestimation

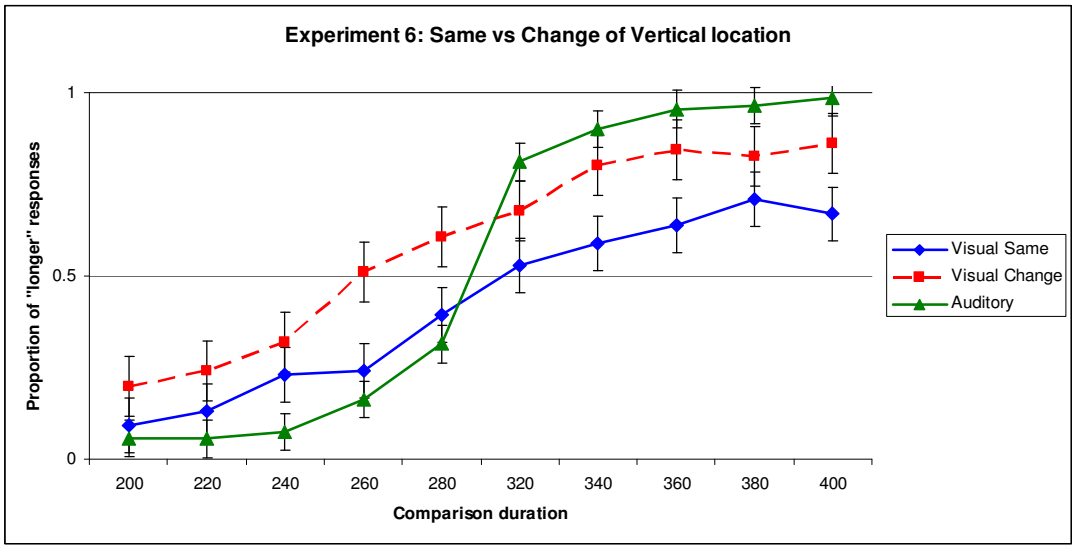


Figure 4.6. Psychophysical functions (mean proportion of LONGER responses plotted against comparison stimulus duration) from the auditory and visual conditions for combined visual *same location* conditions (TT –BB) and visual *change of location* conditions (TB –BT).

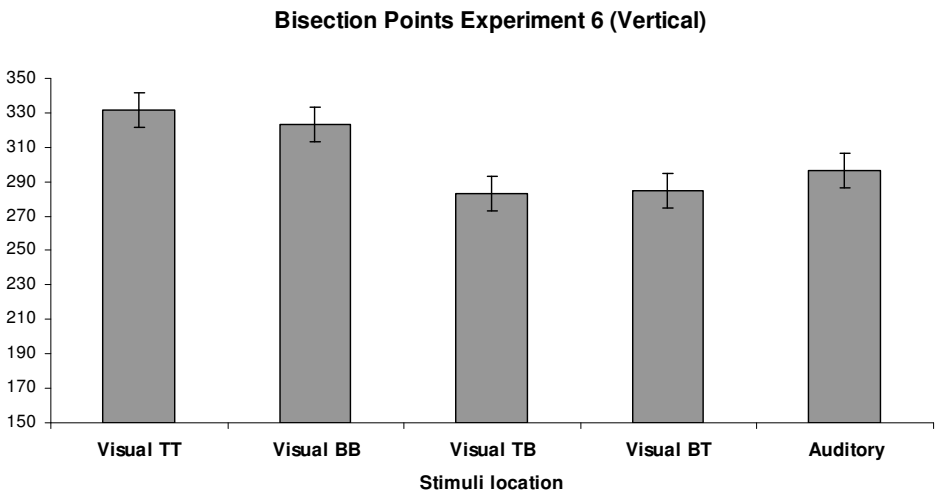


Figure 4.7. Bisection points for all four visual location trials compared to the auditory bisection point with participants underestimating the visual *same location* trials (TT – BB) compared to auditory and overestimating the visual *change of location* trials (TB – BT) compared to auditory.

4.2.3 Interim Discussion of Experiment 6

Experiment 6 replicated the results of the previous experiment with the overestimation of *change of location* visual trials, confirming the hypothesis that it is the change of spatial location at the visual modality that mainly affects participants' performance. In both present experiment and Experiment 3, when participants were presented with same location standard and comparison stimuli, underestimation of visual trials in comparison to the auditory was observed.

The performance across all measures was similar to Experiment 3, indicating that it was not the right – left presentation manipulation that led to the results observed in Chapter 3.

The only difference with Experiments 2 and 3 of the previous chapter was that the overestimation of the *change of location* trials was not found to be larger in Experiment 6 than Experiment 5.

Table 4.3. Mean Error and RT performance for shorter and longer duration ranges across all conditions for Experiments 5 & 6

Condition			Exp. 5		Exp. 6	
		Duration range	Errors %	RTs (ms)	Errors %	RTs (ms)
Visual	Same	Shorter	-	-	24.6*	573
		Longer	-	-	38.1*	561
	Change	Shorter	41.0**	791**	40.7**	626**
		Longer	23.5**	695**	22.7**	540**
Auditory		Shorter	12.5	865	12.0	674
		Longer	13.0	846	10.0	642

* p<0.05 for difference between Shorter and Longer duration range conditions, **p<.01 for difference between Shorter and Longer duration range conditions

4.3 General Discussion: Experiments 5 and 6

The central question of the two experiments presented in this chapter was whether vertical presentation of visual stimuli is going to yield the same effects as horizontal presentation (right versus left) in Experiments 1-4.

Two main effects of location appeared in the experiments presented in Chapter 3:

1) overestimation of *change of location* (LR and RL location conditions) visual trials when visual and auditory trials were intermixed in the same session,
2) underestimation of the *same location* visual trials (RR and LL location conditions); this effect was observed even when there was no mixed modality presentation (Experiment 4).

In Experiments 5 and 6 vertical presentation of visual stimuli was used (top and bottom of the screen). Both overestimation of change of location trials (TB – BT) (in both Experiments 5 and 6) and underestimation of same location trials (TT – BB) (in

Experiment 6) were replicated. These findings made clear that these effects had nothing to do with the right – left presentation that was used in the previous experiments.

Apart from the psychophysical measures that yielded similar results, participants' reaction time performance was also similar to Experiments 2 and 3. Participants were faster in the longer duration range and this difference between ranges was particularly prominent for the visual change of location trials. Therefore, Experiments 5 and 6 seem to support the hypothesis that shifts of spatial attention underlie the overestimation bias of the *change of location* trials and that there is a mechanism which adds a duration in order to compensate for the loss of time during these shifts (see Chapter 3, section 3.5.1).

It has to be noted that there is a difference between the size of the overestimation in Experiments 2 & 3 and the Experiments 5 & 6. Whereas, the size of the overestimation was higher in Experiment 3 compared to Experiment 2 (30 ms versus 15 ms) – a finding that was attributed to Experiment's 3 higher cognitive load because of the uncertainty about where the second stimulus is going to appear – there was no difference between the size of overestimation between Experiments 5 and 6. In both cases participants' overestimation bias ranged between 20 to 25 ms. A difference between the procedure of the experiments presented in the previous chapter and the current ones was the way that auditory stimuli were presented. Whereas in the previous chapter there was left and right monaural presentation of sounds, here there was just one auditory condition involving binaural presentation of sounds. This sound presentation could lead potentially to a less demanding task. However, the accuracy performance of participants was not higher than in the

previous experiments. Neither performance in any of the other measures had a different pattern than the one in Experiments 2 and 3, suggesting that the side of sound presentation did not affect participants' performance. Thus, it seems unlikely that the presentation of the sounds was the critical factor that led to the differences between the sizes of overestimation.

A contributing factor to the absence of a difference between the size of the overestimation between Experiments 5 and 6, was that participants overestimated BT location condition to a greater degree than TB location (18 versus 36 ms) in Experiment 5 (whereas there was no difference between participants' bisection points in these two locations in Experiment 6). In addition, the difference in RTs between shorter and longer range in Experiment 5 was larger (around 100 ms) than the one in Experiment 2. Interestingly, this RT difference was more similar to the one observed in Experiments 3 and 6. Despite the fact that it is not clear why this greater overestimation of BT visual trials took place, the close relationship between the RT performance and the size of the overestimation bias is emphasized by the present data.

Moreover, the modality effect on reaction time performance that was observed in Experiments 2 and 3 was replicated in both experiments presented on Chapter 4; participants were significantly faster in visual trials compared to auditory. The binaural presentation of sounds in Experiments 5 and 6 did not change this RT effect, ruling out the presentation of sounds in separate ears as an interpretation of the slower reaction times in the auditory trials.

The experiments presented here revealed that it is the *change of the location* and not the position per se of visual stimuli that affected participants' performance.

However, there are still open questions: what role do task demands play in the present effects? Is the appearance of the overestimation bias due specifically to modality mixing or rather to the more general cognitive load of the task? When does the underestimation of *same location* trials take place? Is there a single or different mechanisms underlying overestimation and underestimation biases? The experiments presented in the following chapter shall attempt to provide answers for the above questions.

4.4 Summary

The experiments presented in Chapter 4 investigated the role of vertical presentation of visual stimuli on visual and auditory temporal judgments. Although an effect of location per se – top versus bottom presentation – was not shown, overestimation of *change of location* trials and underestimation of *same location* trials was found, in line with the results of the experiments presented in the previous chapter. Therefore, the present findings supported the hypothesis that the overestimation and underestimation biases are not related to the right/left presentation. The remaining open questions about the mechanisms underlying the present effects are going to be explored in the two experiments presented in Chapter 5.

Chapter 5 –

AN INVESTIGATION OF THE EFFECTS OF ATTENTIONAL DEMANDS AND MIXING OF MODALITIES ON VISUAL TEMPORAL JUDGEMENTS

This chapter presents two additional experiments with the purpose of further investigating the causes of the overestimation and underestimation biases in visual temporal judgements that were observed in the previous two chapters. The experiments discussed in Chapter 4 made it possible to rule out the right – left presentation of stimuli as responsible for the above distortions of perceived duration. A central question, as mentioned in the general discussion of Chapter 3, concerns the main factors causing the overestimation of *change of location* visual temporal judgments (see section **3.5.1**); is it a result of a general effect of higher cognitive load, or is it specific to modality mixing?

5.1 Experiment 7 – Introduction

Experiment 7 investigated whether the overestimation of *change of location* visual stimuli is a result of increased cognitive load or of specifically mixing visual and auditory temporal judgments. Such overestimation was observed only in experiments in which presentations of both visual and auditory temporal judgments were randomly intermixed within the same session (Experiments 2, 3, 5 6). In contrast, when visual trials were presented blocked – either only *change of location* trials

(Experiment 1) or *change of location* trials intermixed with *same location* visual trials (Experiment 4) – the overestimation bias was not observed.

A mechanism, adding a specific duration in the case of visual change of location, was proposed at the general discussion of Chapter 3. The purpose of this mechanism was suggested to be a compensation for the time lost during switching of spatial attention from the one location to another. This mechanism seems to function effectively when only visual temporal judgments are required. However, when visual and auditory temporal judgments are required within the same session, then the overestimation of *change of location* manifests.

Two different explanations have been proposed for this effect. According to the first explanation, the overestimation effect is a more general effect of higher attentional load of the mixed modality discrimination paradigm (due to modality switching costs). Task's cognitive load has been shown to directly influence duration judgments and/or to mediate the effect of spatial attention on perceived duration (Block, Hancock & Zakay, 2010; Cicchini & Morrone, 2009). Cognitive load has been manipulated in various ways in different experimental studies with task switching being one of them. Experiments 2, 3, 5 and 6 involved modality switching. Hence, apart from having to monitor two locations and shift their attention between them participants also had to switch their attention between modalities. Previous studies have shown that this disrupts participants' performance in spatial discrimination (Murray, De Santis, Thut & Wylie, 2008).

Alternatively, the overestimation could specifically be a result of mixing the two modalities in one session. In this case the bias would appear due to difficulties in switching the attention between locations and comparing or integrating the visual and

auditory temporal output (which might take place automatically when different modality trials are presented in the same session).

Experiment 7 was conducted in order to test these two competing explanations. It involves the combination of visual duration discrimination trials with visual size discrimination trials. Thus, instead of mixing visual and auditory duration judgments, visual duration judgments were mixed with visual size judgments. If the general cognitive load explanation were more appropriate, then we would expect to replicate the overestimation of *change of location* trials that was observed in Experiments 2, 3, 5 and 6. In contrast, if the overestimation of *change of location* trials is not observed, then the modality mixing hypothesis will be supported.

The structure of the Experiment 7 was similar to the structure of Experiment 3; the only difference being that in the place of auditory duration comparison trials, visual size comparison trials were used. Four location conditions were included in this experiment: two *same location* and two *change of location*. The duration trials' stimuli were presented on the horizontal meridian (left and right of fixation as in Experiment 3) and the size trials' stimuli were presented vertically (top or bottom of the screen as in Experiment 6).

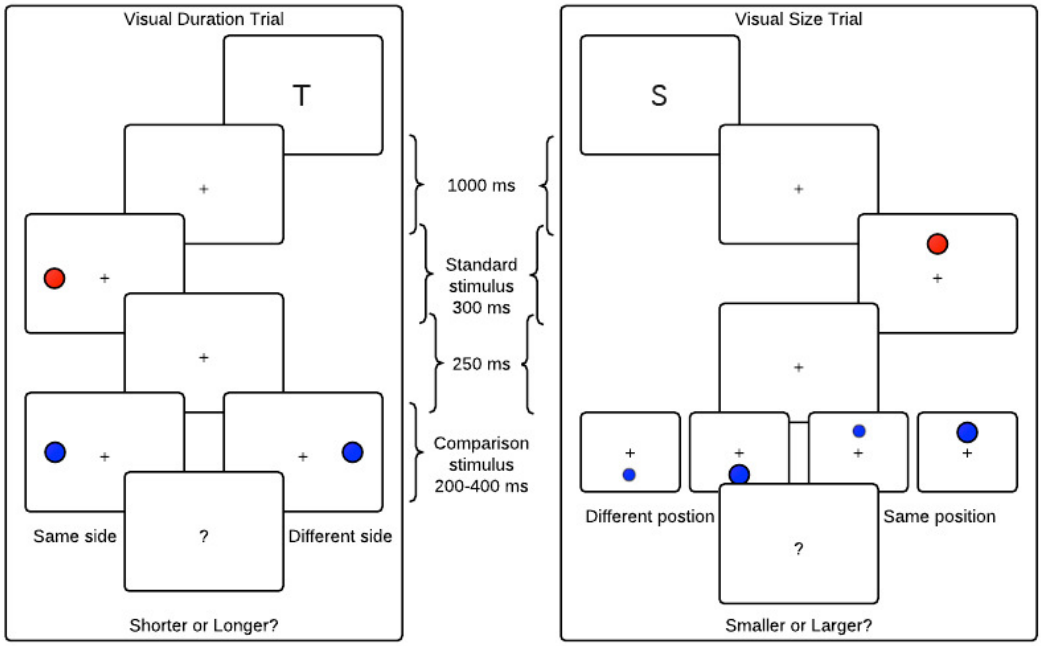


Figure 5.1 Time course & stimuli of Experiment 7. The duration for both the standard and comparison stimuli for the visual size task is 300 ms.

5.1.1 Methods

A. Participants

Twelve female and ten male students of the University of Edinburgh from 18 to 27 years in age (M = 22.9, SD = 3.3) participated in a single experimental session that lasted approximately 45 minutes. They were paid £5 for taking part in the experiment. All of them were right-handed and had normal hearing and normal or corrected-to-normal vision. The data of 3 participants were excluded from the analysis due to high level of inaccurate responses (their average percentage of errors was 2 standard deviations higher than the average of the sample). Therefore, data from 19 participants were analysed.

B. Apparatus and Stimuli

The apparatus was the same as for the visual trials in the previous experiments. The stimuli were red and blue circles on a white background presented: 1) on the left or the right side of the screen (8° eccentricity) for duration trials or 2) on the top or the bottom side of the screen (8° eccentricity) for the size trials. The width of the circles was 1° for the duration trials and it varied from this standard size by up to ± 17% for the size trials.

C. Procedure

The structure of this experiment was similar to the structure of Experiment 3. The duration trials were identical to the visual trials of Experiment 3. The size trials had the same structure, with the standard stimulus appearing first (on the top or bottom of the screen) and the comparison stimulus second. The standard stimulus was a red circle 30 pixels across and was displayed for 300 ms. The comparison stimulus was a blue circle displayed for the same length of time and varied in diameter from 25 pixels to 35 pixels with a step size of 1 (excluding 30 pixels), so that there were five levels of smaller comparisons and five levels of larger comparisons. After the offset of the comparison stimulus a question mark was presented in the middle of the screen prompting participants to indicate whether the comparison appeared to be smaller or larger than the standard by pressing either “m” or “k” on the computer keyboard. At the beginning of each trial there was a cue that indicated which type of trial was about to begin. A capital “T” was the cue for a time (duration discrimination trial) and a capital “S” was the cue for a size discrimination trial. Participants each performed a total of 640 trials consisting of 320 duration trials

randomly intermixed with 320 size trials. Participants were allowed three evenly spaced breaks during the experimental session in order to rest.

5.1.2 Results

As the present study focuses on participants' duration judgments, only the results from the duration trials will to be reported in detail here. Since error and reaction time analysis did not show significant differences between RR & LL conditions and between LR & RL conditions, the data from these conditions are combined – as in Experiment 3 – and referred to as *same location* condition and *change of location* condition respectively.

A. Error percentages

Participants produced 27% errors in the duration trials and 14.8% in the size trials. Therefore the mean error performance in the size trials was similar to the error performance in the auditory duration trials of the previous experiments (≈ 13%). A repeated measures ANOVA was conducted in the duration trials with location (same vs change) and duration of the comparison stimulus as factors. The ANOVA found a significant effect of location, ($F(1,18)=5.3$, $p<.05$), indicating a higher percentage of errors at the *same location* (28.2%) compared to the *change of location* (25.8%) as well as for duration ($F(3.2,57.9)=26.5$, $p<.001$). The interaction between location and duration, ($F(3.2, 59.1)=7.1$, $p<.001$) was also significant.

Inspection of Figure 5.2 suggests that there is a substantial difference in performance between shorter and longer duration ranges in the *same location* condition whereas there is not so much difference between the shorter and longer

ranges in the *change of location* condition. In order to further investigate this observation an additional ANOVA was conducted with two factors again: location (same versus change) and duration with two levels (shorter versus longer). Apart from the location effect, the duration effect was found to be significant, ($F(1,18)=19.3$, $p<.001$) with participants committing more errors in the longer range (32.5%) than in the shorter range (21.4%). The interaction between location and duration was also significant ($F(1,18)=15.7$, $p<.001$). This interaction indicates that although in the *same location* condition participants made more errors in the longer range (38.1%) compared to the shorter range (18.1%), in the *change of location* condition the error percentages are of comparable size between shorter (24.7%) and longer (26.8%) duration ranges (see also Table 5.3 for mean error percentages across the different conditions). These differences were tested by t-tests conducted as post-hoc tests, whereby only a significant difference between duration ranges in the *same location* condition was found ($t(18)=5.9$,$p<.001$).

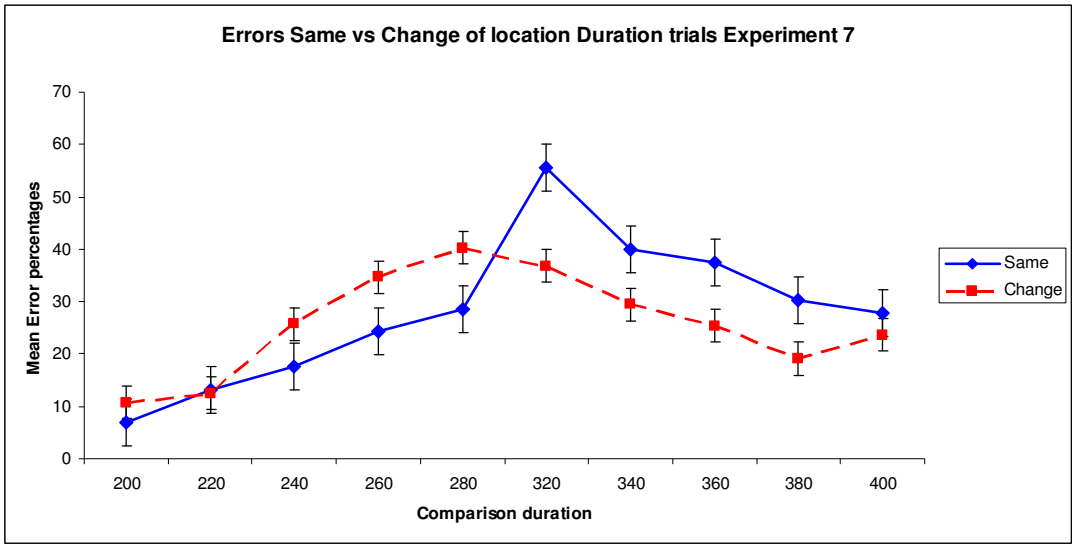


Figure 5.2. Mean Error percentages plotted against comparison stimulus duration from the visual duration trials comparing the performance between *same location* (RR - LL) and *change of location* (LR - RL) conditions.

B. Reaction times

Participants' average reaction times in this experiment were 653 ms for the duration trials and 666 ms for the size trials. A repeated measures ANOVA with two factors, location (same vs change) and duration of the comparison stimulus was conducted in the duration trials. Only a significant effect of duration, ($F(9,162)=3.8$, $p<.01$) was found. Figure 5.3 shows participants' reaction times plotted against comparison stimulus duration.

In order to further investigate the effect of duration, an additional ANOVA was conducted for the visual modality with two factors: location (same versus change) and duration with two levels (shorter versus longer). Duration was found to have significant effect, ($F(1,18)=6.7$, $p<.05$), showing that participants were faster in the shorter range (630 ms) than in the longer range (676 ms). Although the interaction between location and duration, ($F(1,18)=2.7$, $p=.118$) was not significant,

inspection of the RT values (see Table 5.3) suggests that the difference between shorter and longer ranges is more prominent for the *same location* condition (614 ms vs 688 ms respectively) than for the *change of location* condition where the RT values were very similar for both duration ranges (646 ms vs 665 ms). The t-test on the *same location* condition was significant, ($t(18)=2.6$, $p<.01$) whereas no significant differences between shorter and longer range were found for the *change of location* condition by the t-test.

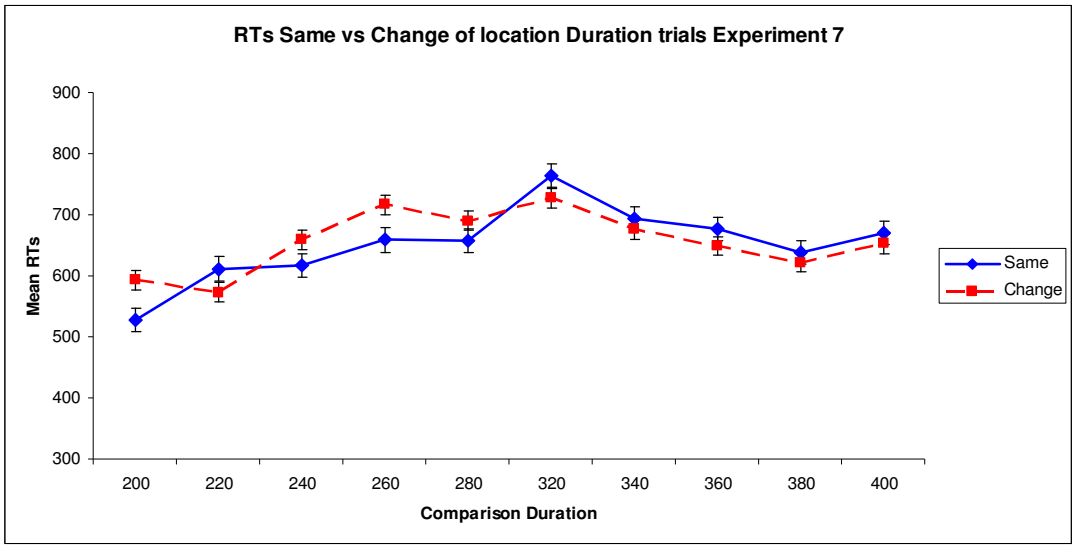


Figure 5.3 Mean Reaction times plotted against comparison stimulus duration from visual duration trials comparing the performance between *same location* (RR – LL) and *change of location* (LR – RL) conditions.

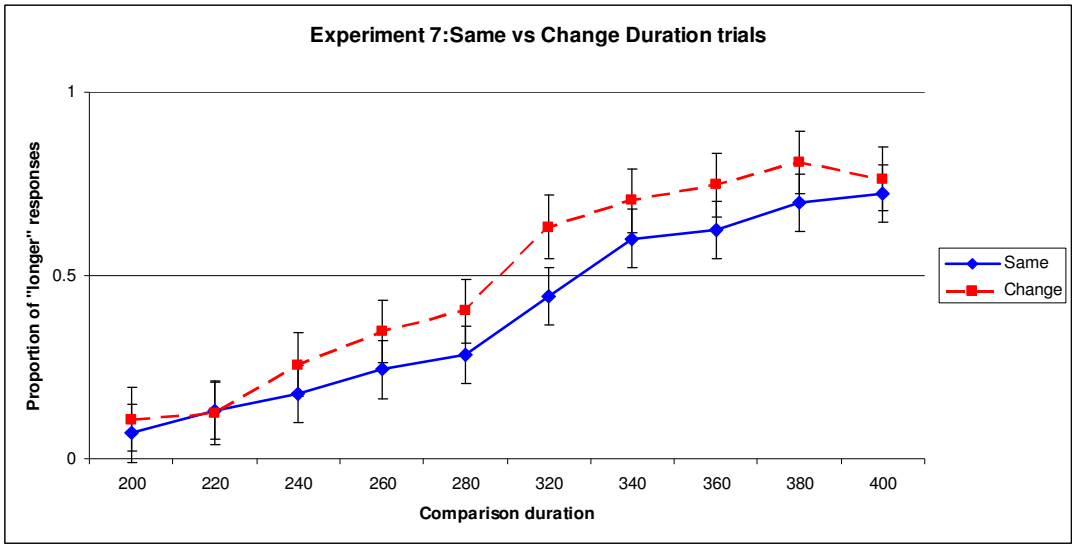
C. Psychophysical functions

Figure 5.4 shows the psychophysical functions in the duration trials. Inspection of this figure suggests that the proportion of *longer* responses increases with the comparison stimulus duration. Also, a rightward displacement of the *same location* function is observed. A repeated measures ANOVA was conducted with two factors

(location, comparison duration). The ANOVA found effects of location, ($F(1,18)=17.5$, $p<.001$) and stimulus duration, ($F(2.3, 40.9)=102.8$, $p<.001$). There was found lower proportion of *longer* responses in the *same location* trials compared to the *change of location*. Also the interaction between location and duration was found to be significant, ($F(5.3,95.7)=2.6$, $p<.05$).

In order to further investigate the differences between the psychophysical functions in the different conditions, the individual bisection points and Weber ratios were calculated as shown in Table 5.1. Inspection of the values in this table reveals a difference between *same location* and *change of location* conditions, with the *same location* conditions (RR & LL) having larger values than the *change of location* (LR & RL). This difference suggests an underestimation of *same location* trials compared to the *change of location* trials. An ANOVA with two factors – type of location (same versus change) and location per se (right versus left) – was conducted on participants mean BPs. Only the effect of type of location was found to be significant, ($F(1, 18)=19.38$, $p<.001$), with participants significantly underestimating the *same location* trials in comparison to the *change of location* (331 ms vs 302 ms).

The Weber ratio values are also shown in Table 5.1. Inspection of the values shows no differences between the conditions as was confirmed by statistical analysis. Participants' temporal sensitivity was found to be very similar between the different conditions.



Figures 5.4. Psychophysical functions from the visual duration conditions of Experiment 7. A rightward displacement of the *same location* condition function indicates underestimation of duration.

Table 5.1. Bisection points and Weber ratios from duration trials from Experiment 7

Condition	BP (mean)	WR (mean)
LR	303	0.085
RL	302	0.084
RR	325*	0.085
LL	337**	0.076

*p<0.05 significant underestimation, **p<0.01 significant underestimation

5.1.3 Interim discussion of Experiment 7

Overestimation of *change of location* visual trials was not observed in Experiment 7. Bisection points in both *change of location* conditions were very similar to the duration of the standard stimulus, indicating that there was neither overestimation nor underestimation bias in these conditions. Reaction times were also very similar between the shorter and longer range in the change of location, confirming the absence of the effect (in all the previous experiments that the overestimation bias was

observed, participants' had also significantly faster reaction times in the longer range in visual *change of location* trials).

Therefore, the results of Experiment 7 supported the hypothesis based on the mixing of visual and auditory modalities. Switching between duration comparison and size comparison trials did not result in the same effect as switching between modalities, despite the fact the auditory temporal judgments and visual size judgments yielded similar error performance, suggesting that task difficulty was not a confounding factor in Experiments 2, 3, 5 & 6.

Although overestimation of *change of location* trials was not replicated in the present experiment, underestimation of *same location* trials was still observed. Hence, this underestimation of *same location* visual judgments appears to be very consistent across experiments and not dependent on the modality mixing of the trials. In contrast, it seems to appear in every instance in which visual *same location* and *change of location* trials are mixed within one session (the underestimation did not appear in a control experiment where visual *same location* trials were presented in a separate block).

In this experiment, *same location* trials, apart from underestimations, also produced longer reaction times and higher percentage of errors in the longer than the standard duration range. Why though, do participants give more shorter responses when the second stimulus appears in the same location as the first? Could it be explained as an effect of adaptation (see section **2.2.3**, Chapter 2) which appears when people have to compare the output from two different clocks (*change of location*) or the same clock (*same location*)? Stimuli that are presented to the adapted region of the visual field have previously been found to appear shorter than those

displayed on the non-adapted location (Johnston, Arnold & Nishida, 2006). Or alternatively is it just an effect of paying less attention in the trials where stimuli appear at the same location?

One last experiment was conducted attempting to clarify some of the remaining questions, adopting exactly the same structure as Experiment 3 (mixed visual – auditory duration discrimination) but using a longer inter-stimulus interval (ISI). The aim of this experiment was to determine whether underestimation of *same location* trials and overestimation of *change of location* trials would still appear given a longer ISI.

5.2 Experiment 8 – Introduction

The results of our previous experiments showed that the overestimation of the *change of location* trials appeared only when visual trials were mixed with auditory trials within the same session. The manifestation of the overestimation bias was attributed to the over-activation of a mechanism, which corrects for the error in subjective duration incurred during spatial attention shifts (by adding a specific duration to the visual *change of location* trials). The over-activation of the error-correction mechanism is triggered by the mixing of the visual and auditory temporal stimuli, which might take place automatically when different modality trials are presented within the same session. When, in contrast, visual change of location trials are presented separately, then the activity of the error correction mechanism is not noticeable (there is no overestimation bias).

However, does this over-activation of the error correction mechanism always occur when there is intermixed presentation? The ISI that was used in the previous experiments presented here was quite short (250 ms). It could be the case that when the presentation of the standard and comparison visual stimuli is so close, there is not enough time to fully process them. If instead the ISI is longer, this could facilitate more independent processing of visual stimuli which is less likely to be interfered by the auditory temporal information.

Therefore, a longer ISI was used in Experiment 8 that was involving presentation of visual and auditory duration judgments within the same session. The duration of the ISI was 1250 ms - one second longer than the ISI that was used in the previous experiments and well above the limit of the visual sensory memory which lasts around 500 ms (Plummer & Humphrey, 2008).

An additional purpose of this experiment was to examine the effect of the longer ISI on the underestimation of the *same location* visual trials. Is the underestimation still going to appear with a longer ISI? The way that the longer ISI influences the temporal judgments of *same* location and *change of location* visual trials could potentially clarify whether similar or different mechanisms underlie their processing.

5.2.1 Methods

A. Participants

Nine female and eleven male students of the University of Edinburgh from 18 to 29 years in age (M = 23.6, SD = 3.5) participated in a single experimental session that lasted approximately 45 minutes. They were paid £5 for taking part in the

experiment. All of them were right-handed and had normal hearing and normal or corrected-to-normal vision. The data of one participant were excluded from the analysis due to high level of inaccurate responses (their average percentage of errors was higher than 2 standard deviations higher than the average of the sample). Therefore, data from 19 participants were analysed.

B. Apparatus and Stimuli

The apparatus was the same as in Experiment 3.

C. Procedure

The structure of this experiment was identical to structure of Experiment 3, involving randomly mixed visual and auditory trials and four location conditions (RR, LL, LR & RL). The only difference was that the ISI – the interval between the presentation of the standard stimulus and the comparison stimulus when only the fixation point remains in the middle of the screen – lasted for 1250 ms.

5.2.2 Results

As error and reaction time analysis did not show significant differences between RR & LL conditions or between LR & RL conditions – similarly to the previous experiments – the data from these conditions are combined and referred to as *same location* condition and *change of location* conditions respectively.

A. Error percentages

Participants performed with 29.5% errors in the visual trials and 13.2% in the auditory trials. A repeated measures ANOVA conducted with modality, location (same vs change) and duration of the comparison stimulus as factors found a significant effect of modality ($F(1,18)=138.8$, $p<.001$), and duration ($F(1.8,33.9)=34.7$, $p<.001$) as well as significant interactions between modality and duration ($F(3,54.9)=6.7$, $p<.001$), and between location and duration ($F(5.5,99.3)=8.4$, $p<.001$). Figure 5.5 suggests that there is a large difference in performance between shorter and longer duration ranges in the visual *same location* condition whereas there is less difference between the shorter and longer ranges in visual *change of location* and auditory conditions.

In order to further investigate this observation another ANOVA was conducted, with the same number of factors: modality, location and duration. The difference here was that duration had two levels instead of ten (shorter than 300 ms versus longer than 300 ms). Apart from the effect of modality, duration was also found to be significant ($F(1,18)=13.7$, $p<.010$), with participants making less errors in the shorter duration range (16.3%) than in the longer range (26.3%). Significant interactions were also found between modality and duration ($F(1,18)=12.8$, $p<.01$), and between location and duration ($F(1,18)=39.5$, $p<.001$). In order to explore these interactions, two additional ANOVAs were conducted, one for visual and one for auditory with two factors: location (same versus change) and duration with two levels (shorter versus longer). Although in the auditory modality no significant differences were found, in the visual modality a main effect of duration, ($F(1,18)=24.4$, $p< .001$), was observed – indicating a higher percentage of errors in

the longer range (37.9%) than in the shorter range (20.9%) – as well as a significant interaction between location and duration ($F(1,18)=33.2$, $p<.001$). This interaction indicates that in the *same location* condition participants had a much higher percentage of errors in the longer range (44.2%) than in the shorter range (16%), whereas in the *change of location* condition this difference between ranges is smaller (25.9% for the shorter range versus 31.7% for the longer range). Only the t-test (conducted as post-hoc tests), for the differences between shorter and longer range, in the *same location* condition, was found to be significant ($t(18)=6.5$, $p<.001$).

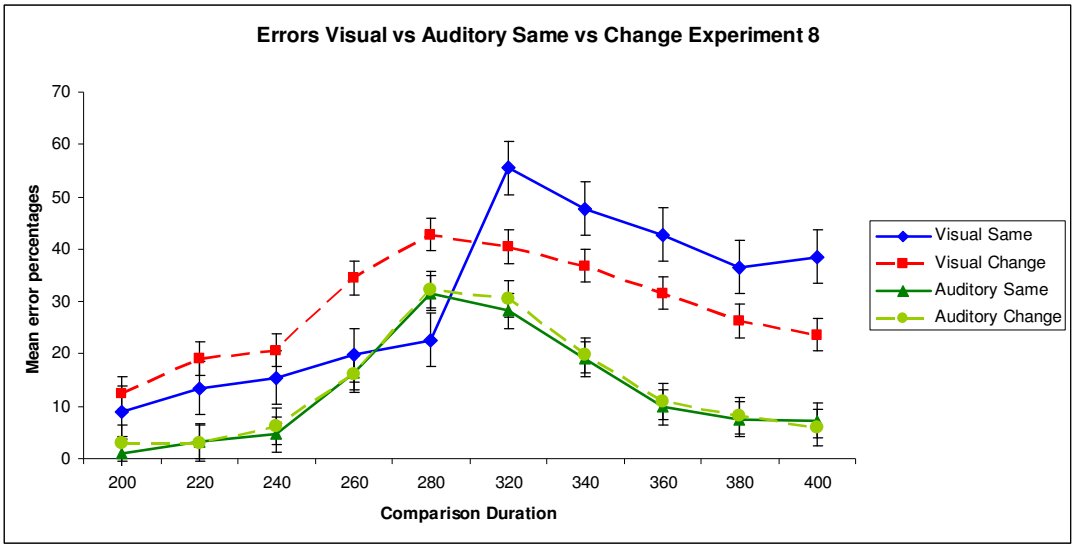


Figure 5.5. Mean Error percentages plotted against comparison stimulus duration from visual and auditory trials and comparing the performance between *same location* (RR – LL) and *change of location* (LR – RL) conditions.

B. Reaction times

Participants' average reaction times in this experiment were 625 ms for the visual trials and 774 ms for the auditory trials. Similarly to all previous experiments involving mixed modality presentation, visual RTs appeared to be shorter than

auditory RTs (as it can be seen also in Figure 5.6). This observation was confirmed by the analysis. A repeated measures ANOVA with three factors (modality, location and duration) was conducted. A significant effect of modality ($F(1,18)=25$, $p<.001$), duration ($F(3.4, 61.7)=15.8$, $p<.001$) and location ($F(1,18) = 12.9$, $p< .01$) – indicating shorter RTs for the *same location* (675 ms) compared to the *change of location* (724 ms) condition – were found. Also, there was a significant interaction between modality and duration ($F(3.9, 71.6)=5.4$, $p=.001$), and a significant interaction between modality and location, ($F(1,18)=4.4$, $p< .05$). Inspection of the means from the different conditions suggested that the interaction between modality and location indicated that the difference between location conditions was significant only for the visual modality. These interactions were further explored in the subsequent analysis.

Two additional ANOVAs were conducted, one for the visual and one for the auditory modality with location (same versus change) and duration range (shorter versus longer) as factors. While in the auditory modality no significant effects were observed, in the visual, the effect of location, ($F(1,18)=10.7$, $p<.01$) found to be significant, indicating shorter RTs for the *same location* (584 ms) than for the *change of location* (665 ms). Furthermore, a trend of an effect of duration was observed, ($F(1,18) = 3.5$, $p = .077$) – suggesting shorter RTs for the shorter duration range (604 ms) than for the longer (645 ms). Despite the fact that the interaction between location and duration, was not significant, inspection of the mean values (see Table 5.3) suggests a larger difference between duration ranges for the *same location* condition (shorter: 554ms, longer: 614 ms => 50 ms difference) than for the *change of location* condition (shorter: 654ms, longer: 677 ms = 23 ms difference). A trend

for an effect of the duration range was found via a t-test comparing shorter and longer ranges for the same location condition, (t(18)=2.2, p=.044).

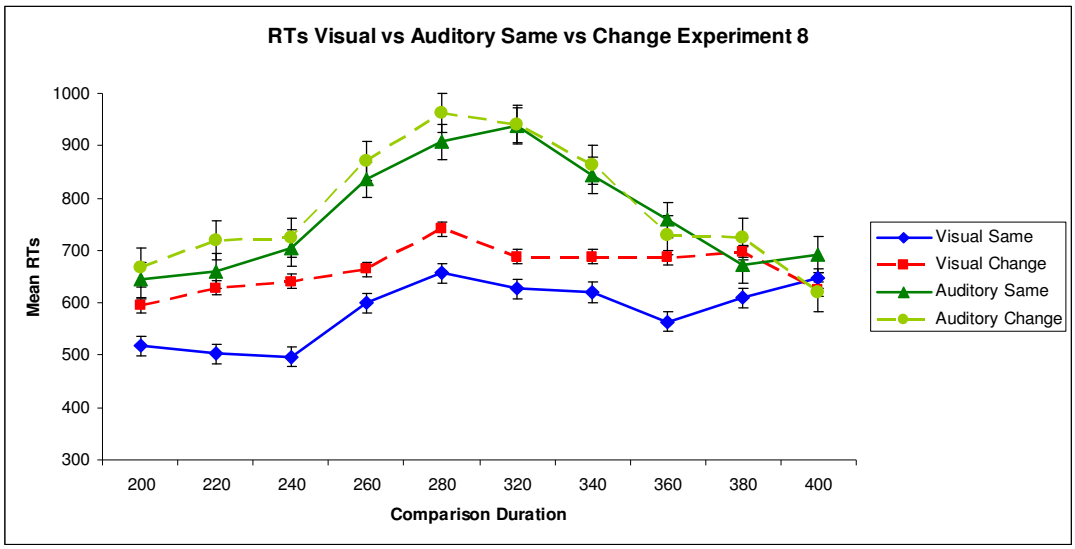


Figure 5.6. Mean Reaction times plotted against comparison stimulus duration from visual and auditory trials and comparing the performance between same *location* (RR – LL) and *change of location* (LR – RL) conditions

C. Psychophysical functions

Figure 5.7 shows the psychophysical functions in the visual and auditory trials with *same location* (RR & LL) trials being combined and *change of location* (LR & RL) trials being combined. A rightward displacement of the visual *same location* function is observed compared to both visual *change of location* and auditory functions. A repeated measures ANOVA was conducted with modality, location and duration as factors revealing main effects of modality ($F(1,18)=13.5$, $p<.01$), (with participants giving lower proportion of *longer* responses in the visual modality than in the auditory), location ($F(1,18)=40.2$, $p< .001$) (with participants giving lower proportion of *longer* responses in the *same location* than in the *change of location* condition)

and duration ($F(2.9,67)=483.4$, $p<.001$), and significant interactions between modality and duration ($F(4.7,85.5)=35.9$, $p<.001$), and between modality and location ($F(1,18)=23.5$, $p< .001$). The interaction between modality and location indicates that the effect of location seems to appear only in the visual modality. Separate repeated measures ANOVAs in the visual and auditory modality were conducted to confirm these observations. The analysis in the visual modality found an effect of stimulus location $F(1,18)=33.6$, $p<.001$), an effect of comparison duration ($F(2.7,49.9)=101.6$) and a significant location by duration interaction ($F(4.5,82)=2.7$, $p<.05$). Participants exhibited a lower proportion of *longer* responses in the *same location* trials compared to the *change of location*. In the auditory modality only the effect of duration was significant ($F(2.7,49.7)=366.4$, $p<.001$).

Bisection points and Weber ratios for the Experiment 8 are shown in Table 5.2. Visual bisection points in the conditions RR and LL are displaced towards the right, indicating underestimation of durations. In contrast visual LR and RL as well as all auditory values are near the standard duration value (300). The within subject ANOVA showed an effect of location ($F(3,54)=16.9$, $p<.001$), an effect of modality ($F(1,18)=16.9$, $p=.001$), and an interaction between location and modality ($F(3,54)=13.2$, $p<.001$). T-tests showed that the value of the BP at the visual RR was significantly larger than the auditory RR ($t(18)=6.7$, $p<.001$), and the visual LL larger than the auditory LL, ($t(18)=3.8$, $p<.001$). Also, visual LL was significantly different than visual RL ($t(18)=4.2$, $p<.001$), as well as visual RR different than visual LR ($t(18)=5.2$, $p<.001$). These differences confirmed that participants tended to underestimate duration in the visual *same location* trials in comparison to *change of location* trials.

Table 5.2 also shows the Weber ratios. Weber ratios between modalities seem again to be very different. This modality effect was confirmed by a repeated measures ANOVA ($F(1,18)=57.9$, $p<.001$). The location effect was not significant. This difference replicated the result that we got in the previous experiments whereby participants had higher temporal sensitivity in the auditory modality.

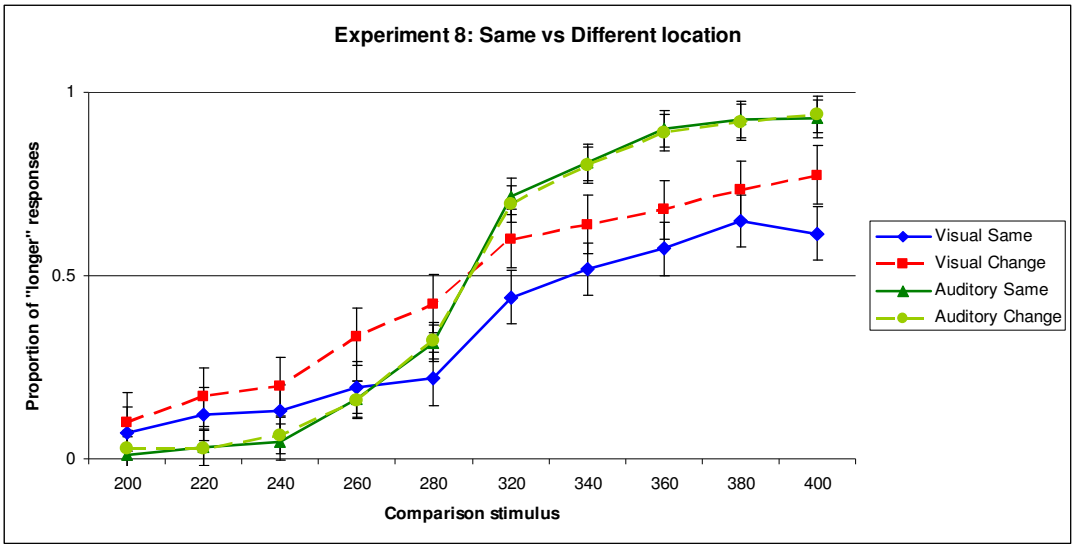


Figure 5.7 Psychophysical functions (mean proportion of LONGER responses plotted against comparison stimulus duration) from the auditory and visual conditions for combined *same location* conditions (RR –LL) and *change of location* conditions (LR –RL).

Table 5.2. Bisection points and Weber ratios from Experiment 8

	Condition	BP (mean)	WR (mean)
Visual	LR	306	0.089
	RL	309	0.098
	RR	354**	0.092
	LL	346**	0.101
Auditory	LR	298	0.037
	RL	307	0.036
	RR	303	0.038
	LL	304	0.038

**p<0.01 significant underestimation

5.2.3 Interim Discussion Experiment 8

The overestimation of *change of location* visual trials was not observed in Experiment 8, despite the mixed modality trial presentation. Hence, it seems that the manipulation of the ISI was critical to participants' performance in *change of location* visual conditions. The use of a longer ISI precluded the appearance of the above bias. Reaction times were quite similar between shorter and longer ranges in the *change of location* visual conditions, in contrast to all the other experiments with mixed visual and auditory presentation (Experiments 2, 3, 5 & 6) where RTs were considerably shorter in the longer than 300 ms duration range compared to the shorter range. The performance in visual *change of location* trials here is actually quite similar to the performance of the these conditions in Experiment 4 – where there was just visual trials, either *same location* or *change of location* – and in Experiment 7 – with mixed presentation of visual duration discrimination and visual size discrimination trials. Thus, the effect of mixed modality on visual change *of location* duration judgments is counteracted by the longer ISI.

In contrast, underestimation of *same location* visual trials is still apparent and it seems to be quite strong (around 50 ms underestimation). Slower reaction times in the longer range for the *same location* visual trials accompany this underestimation, much like in Experiments 4 and 7. Possible interpretations of the underestimation effect shall be discussed on the general discussion of the present chapter. Overall, the performance of participants in the visual trials of Experiment 8, was quite similar to the performance in Experiments 4 and 7.

Table 5.3. Mean Error and RT performance for shorter and longer duration ranges across all conditions for Experiments 7 & 8

Condition			Exp. 7		Exp. 8	
		Duration Range	Errors %	RTs (ms)	Errors %	RTs (ms)
Visual	Same	Shorter	18.1**	614*	16.0**	554*
		Longer	38.1**	688*	44.2**	614*
	Change	Shorter	24.7	646	25.1	654
		Longer	26.8	665	31.7	677
Auditory	Same	Shorter	-	-	11.4	750
		Longer	-	-	14.4	781
	Change	Shorter	-	-	12.1	789
		Longer	-	-	15.0	775

*p<0.05 for difference between Shorter and Longer duration range conditions, **p<0.01 for difference between Shorter and Longer duration range conditions

5.3 Comparison of the two Biases: Overestimation in the *Change of Location* Condition versus Underestimation in the *Same Location* Condition

Inspection of the BPs across experiments suggested that there is a relationship between the magnitudes of the overestimation and underestimation biases, with larger overestimation biases associated with smaller underestimation biases. A correlation between these values might suggest some overlap or other relationship between the mechanisms which cause these biases. Correlational analysis was conducted in order to investigate the above observation. When the two biases were compared within each experiment separately, no significant correlation was found. However, when a mean underestimation and overestimation value were calculated for each experiment (only for the experiments that involved both visual *same*

location and *change of location* conditions: 3, 4, 6, 7 & 8) separately and a Pearson's correlation coefficient was computed to assess the relationship between them an almost significant correlation was found (r=.875, n=5, p=.051). As five observations are too few, a Pearson's correlation coefficient was computed for the individual overestimation and underestimation values across all the five experiments. In this case a highly significant correlation was found between the two biases (r=.313, n=98, p<.001). This correlation indicates that when there is larger overestimation of *change of location* trials, then the underestimation of *same location* trials is smaller and when there is no overestimation bias then the underestimation is larger.

Table 5.4. Summary of experimental conditions and key results

Experiment	Modality presentation	Location condition	Bias Change of Location	Bias Same Location
3	Mixed	LR - RL / RR - LL	28.67**	-21.58*
6	Mixed	TB - BT / TT - BB	16.46*	-27.43**
2	Mixed	LR - RL	15.50*	-
5	Mixed	TB - BT	27.50**	-
8	Mixed Long ISI	LR - RL / RR - LL	-8.14	-50.47**
7	Visual Dual Task	LR - RL / RR - LL	-2.58	-31.25**
4	Only Visual	LR - RL / RR - LL	-4.47	-43.19**
1	Blocked	LR - RL	-1.50	-

*p<0.05, **p<0.01, n.b. negative numbers indicate underestimation, whereas positive numbers indicate overestimation

5.4 General Discussion: Experiments 7 and 8

The results of the experiments presented in Chapter 5 showed that whereas the overestimation of *change of location* visual trials is specific to mixed modality

presentation, the underestimation of *same location* visual trials seems to manifest independently of the exposure to auditory trials within the same session.

5.4.1 Overestimation of visual *change of location* trials

Experiment 7 ruled out the general increase of tasks' attentional demands as a sole explanation of the overestimation bias of *change of location* visual trials. The overestimation bias did not appear when participants had to switch their attention between duration and size discrimination, in contrast to the experiments involving modality switching (Experiments 2, 3, 5 & 6). Thus, it was presumed that exposure of participants to both auditory and visual duration trials within the same session is a necessary requirement in order for this bias to appear. In the General discussion of Chapter 3 was suggested that when participants need to shift their transient attention between two locations in order to make a temporal judgement, a duration is being added in order to compensate for the loss of time during this shift. When there is single modality (visual) presentation, this mechanism is not noticeable – suggesting that it is effective and results in non biases. However, when both visual and auditory trials are presented within the same session, then this mechanism is triggered too strongly and results in the overestimation biases observed in Experiments 2, 3, 5 and 6. Thus, it seems that an automatic mixing/comparison of visual and auditory temporal stimuli occurs when they are presented within the same session despite the fact that the task does not require comparisons between visual and auditory duration judgments. This idea seems analogous to the hypothesised "memory mixing" effect which takes place when participants are exposed to visual and auditory trials in the same session (Penney, Gibbon & Meck, 2000). When mixed modality presentation is

involved, previous studies have found longer judgments of auditory stimuli in comparison to visual ones (Wearden, Todd & Jones, 2006). This constitutes the opposite effect to the one found in the mixed modality experiments presented in Chapters 3 and 4. The overestimation of auditory stimuli in these previous studies was attributed mainly to the auditory "clock" running faster than the visual (or alternatively, if a central amodal temporal mechanism is assumed, then this mechanism is running faster for auditory than for visual stimuli).

It is suggested that in the experiments where there is both *change of location* and mixed modality presentation, the mechanism that compensates for the loss of time occurring during spatial attention shifts, is over-correcting as a result of over-estimating the error. This overestimation of the error is attributed to the interference from the auditory duration representations.

However, when a longer ISI was used in Experiment 8 (1250 ms: 1 sec longer than the ISI that was used in the previous experiments), the overestimation bias disappeared. But why did the effect disappear despite the fact that there was still a mixed modality presentation? A possible interpretation is that in mixed modality presentation, when participants have to switch between locations, and the ISI is short, there is not enough time for processing and therefore the visual duration judgments rely on the auditory judgments (or an integrated representation of visual and auditory output). In contrast, when there is a larger ISI then visual stimuli are processed independently from auditory and therefore there is no observable overestimation bias. Thus, it seems that with smaller ISIs an automatic integration of visual and auditory information takes place; when the ISI gets larger then the temporal processing takes place independently in the visual domain.

Previous studies have shown some evidence for interference from auditory durations on visual temporal judgments. For instance, Chen & Yeh (2009) found expansion of visual stimuli duration when they are presented simultaneously with auditory stimuli that have equal physical duration. Moreover, in cases of conflict, audition often seems to dominate vision in the subjective perception of duration (Burr, Banks & Morrone, 2009). A recent study investigated the interactions between visual and auditory modality in duration judgments by presenting the participants with two sequential stimuli (visual or auditory) accompanied by distractor stimuli of the opposite modality (Klink, Montijn & van Wezel, 2011). The task was to judge which one of the stimuli was longer. The results showed that visual stimuli that were paired with auditory distractors of equal or longer duration were overestimated. In contrast, visual distractors did not affect the performance of auditory duration judgments, a finding that supports the dominance of the auditory modality for temporal processing. The results of Klink, Montijn & van Wezel's study were interpreted in terms of SET (Scalar Expectancy Theory), by adding a cross-modal component to it. Thus, apart from having a pacemaker for visual stimuli and a pacemaker for auditory stimuli, there is also a cross-modal pacemaker –running under audiovisual conditions –which is mainly dominated by the auditory rate. However, the circumstances under which the crossmodal grouping takes place within this model are still unclear.

Hence, in the present experiments, as the brain already struggles to compensate for the change of the location, the crossmodal grouping is potentially favoured when the ISI is short and so the visual temporal judgements rely on the

more reliable auditory ones. The auditory judgments, being the more reliable ones seem also to be less affected by the modality and location manipulations.

5.4.2 Underestimation of visual *same location* trials

In contrast to the absent overestimation bias in the *change of location* trials, the underestimation of *same location* trials was noticeable in both Experiments 7 and 8. After conducting these experiments, it is evident that the underestimation of *same location* visual trials is not caused by the mixed presentation of modalities, as it was first thought after conducting Experiment 3. Underestimation of *same location* trials was observed in Experiments 4 & 7 where no auditory judgments were required. Interestingly, it seems that the underestimation effect was larger in the experiments where only visual trials were presented, compared to experiments that involved mixed modality presentation. Thus, while in Experiments 3 and 6 (mixed modality presentation) mean underestimation ranges between 20 ms and 27 ms, in Experiment 4 they were around 43 ms and in Experiment 7 around 32 ms.

Another interpretation of the underestimation bias would be to explain it as an adaptation effect. Adaptation to visual flicker or to drifting motion was found to reduce the subjective duration of visual stimuli presented to the adapted region of the visual field, but not of the stimuli that were presented to the un-adapted region (Johnston, Arnold & Nishida, 2006; see section **2.2.3**). In fact, the opposite trend (overestimation) was observed for the stimuli that were presented to the un-adapted region, an effect which is compatible with the present results (underestimation of *same location* conditions and overestimation of *change of location* conditions). The adaptation effect on subjective duration suggests the existence of spatially localised

components for the perception of duration (at least for visual stimuli). Adaptation seems that could have noticeable effects after even tens of milliseconds (Kohn, 2007). However, although the present results seem analogous to the adaptation effect, the fact that the standard stimulus is a steady circle makes the adaptation explanation less plausible. Furthermore, if the adaptation hypothesis were valid, then we would expect that the use of a longer ISI should reduce the effect of adaptation (resulting in smaller or non underestimation). Nevertheless, the opposite result was observed in Experiment 8, where a longer ISI was used; participants' underestimation of *same location* visual trials was even larger than in the previous experiments at around 50 ms. Hence, this finding rules out the adaptation hypothesis.

The underestimation of the comparison stimulus in the *same location* conditions seems at first to be compatible with the results of previous studies that have reported underestimation of empty intervals (in contrast to filled intervals aswere used in the present study) when they are preceded by another brief interval, a phenomenon known as "time shrinking" (Arao, Suetomi, Nakajima, 2000). A similar effect is the duration expansion of the first stimulus in a series of two sequentially presented empty stimuli (Kanai & Watanabe, 2006). Underestimation of the second stimulus when preceded by another short stimulus has been also found for filled intervals in experiments that used the temporal generalization paradigm – which involves sequential presentation of two stimuli of which participants have to judge whether the second was presented for the same, shorter or longer duration than the first (Wearden, Parry & Stamp, 2002; Wearden & Ferrara, 1993). In these experiments a bias towards judging the comparison stimulus as shorter than the first (or the first longer than the comparison) – a type of time-order error (TOE) – led to

fewer *longer* responses, as was the case for our visual *same location* conditions where a significantly lower proportion of *longer* responses was found. This underestimation effect on the above studies has been shown to disappear with longer ISIs.

Eagleman & Pariyadath, (2009) interpreted these effects as evidence of repetition suppression which recovers with time (the subjective duration of a stimulus reflects the magnitude of the neural response to the stimulus, thus repeating a short stimulus leads to a reduced amplitude neural response and therefore compression of the duration of the second stimulus – see section **1.4.2.***B*). This recovery from the repetition suppression resembles the reset period of the SDN networks (see section **1.4.2.***A*). According to the SDN networks, the subjective duration of a stimulus depends on the state of the network at the specific moment of time. In tasks that involve the comparison of two sequentially presented stimuli – as in the duration discrimination paradigm, which was used in all the experiments presented in this thesis – the presentation of the second stimulus can be affected by the presentation of the first which can potentially lead to biases in perceived duration (Karmakar, 2011). Nevertheless, if the ISI is long enough, the network can reset and return to its baseline state. This reset time for SDN networks was estimated to be around 500 ms, duration well bellow the ISI interval in Experiment 8 (Buonomano, Bramen & Khodadadifar, 2009). Therefore, according to all the above theories, a longer ISI should lead to a reduction of the underestimation bias instead of the even larger compression that was observed in Experiment 8. Hence, neither temporal shrinking of the second stimulus nor repetition suppression can adequately explain the present results.

In all the experiments where underestimation of the *same location* visual trials was observed, there were intermixed presentation of *same location* and *change of location* visual trials. The results of a control experiment that involved blocked presentation of *same location* and *change of location* visual trials revealed no significant underestimation of the *same location* conditions (the BP value in the same location condition was less than 310 ms – so less than 10 ms of underestimation – which was not found to be a significant bias). It may be that less attention is paid to visual stimuli appearing on the same location in comparison to the stimuli that are changing location and that this leads to underestimations of the *same location* trials.

Interestingly, the two biases (underestimation of *same location* and overestimation of *change of location*) are negatively correlated. Comparing the average biases for each experiment as well as comparing the individual biases from all the experiments showed significant negative correlations between underestimation and overestimation. Thus, in Experiments 3 and 6, which involved mixed modality presentation and produced overestimation of *change of location* trials, there was less underestimation of *same location* trials and in Experiments 4, 7 and 8 where there was no noticeable overestimation of *change of location* trials, the underestimation was larger. Especially, in Experiment 8 where the larger underestimation bias is observed (53 ms) a slight underestimation (8-9 ms) – although not significant – is also observed in the visual *change of location* condition.

Furthermore, in Experiments 4, 7 and 8 where larger underestimation was observed, there was also a significant difference in RT performance between shorter and longer duration ranges in the *same location* trials; participants were significantly faster in the shorter range compared to the longer. This difference between ranges in

RT performance is not observed for Experiments 3 and 6. In contrast, in the Experiments 2 and 5 (where there were only *change of location* trials), a significant difference in RTs is observed between duration ranges with participants being significantly faster in the longer range.

Thus, it seems that two different mechanisms underlie these two biases; when the one is more active (overestimation) the other one is less active (underestimation). It could be hypothesized that the underestimation is a result of less attention paid to the *same location* when compared to *the change of location* condition. However, when the other factor, namely the mixing of modalities, is involved, then it not only affects the *change of location* condition but also the *same location* condition. As a result, overestimation is observed in the *change of location* condition, where previously there was not noticeable bias, whereas in the *same location* condition, the underestimation effect is reduced. The mean overestimation bias in Experiments 3 and 6 (involving mixed modality presentation) is around 22 ms and the mean underestimation is 24 ms. In contrast the mean underestimation between Experiments 4, 7 and 8 (that do not involve auditory temporal judgments or in the case of Experiment 8 there is a long ISI), the mean underestimation bias is 42 ms. The difference between the mean underestimation in these three experiments and the mean underestimation bias in Experiments 3 and 6 is around 18 ms which is a similar value to the mean overestimation (22 ms), which suggests that it could be the same mechanism responsible for both the overestimation bias and the decrease in underestimation.

Finally, another explanation, quite similar to the previous one but focusing on the role of local temporal mechanisms is the following; if temporal processing occurs

separately for distinct locations – at least for visual stimuli –, then in the experiments with both *same location* and *change of location* trials, in some trials the system has to compare the output from one position and/or clock and in others it has to compare the output from two separate temporal mechanisms/clocks. The comparison of the output from a single temporal mechanism results in underestimations of duration when compared to cases where outputs from two different "clocks" need to be compared. However, when the auditory channel is also involved, this leads to an automatic combination of the outputs of the different modality clocks and differential biases are observed.

5.4.3 Visual and Auditory differences in RTs

In Experiment 8, as in all previous experiments that involved both visual and auditory trials within the same session, auditory reaction times are slower than visual ones. Thus, in contrast to the psychophysical measures that were affected by the longer ISI, the modality difference in reaction time performance was unaltered. Participants were around 150 ms faster overall in the visual modality than in the auditory. Reaction times seemed to be the only measure of participants' performance that was affected by any of the manipulations that that were made in the present experiments. Thus, although temporal precision and accuracy remain higher for auditory temporal judgments than for visual, auditory reaction times are slower. As it was mentioned in the previous chapters slower RTs in the auditory modality seem inconsistent with results obtained by N'Diaye et al., (2004). Also, Eagleman and Pariyadath (2009) refer to reaction time differences between visual and auditory temporal stimuli, suggesting that auditory stimuli are both perceived as longer than

visual and support shorter reaction times than visual stimuli. The most plausible explanation for the present results seems to be related to differences in memory capacity between the different modalities. Visual sensory memory degrades quicker (after around 500 ms) than the auditory sensory memory (which lasts 4 seconds). Moreover, there is some evidence for an advantage of short-term memory for auditory temporal stimuli compared to visual temporal stimuli (Guttman, Gilroy & Blake, 2005). Given that in the present experiments the task was quite complicated (especially the visual duration discrimination), participants may give up and respond quicker in the visual modality compared to the auditory – as there is little possibility to improve their performance.

5.5 Summary

Chapter 5 presented two experiments which investigate the contribution of general cognitive load and ISI in the manifestation of the observed overestimation and underestimation biases. Overestimation of visual *change of location* temporal judgments was found to be specific to mixed modality presentation and was attributed to spatial attention shifts combined with an aspect of cross-modal integration. In contrast, the underestimation of *change of location* trials was found to be stronger either when there was a mixed modality presentation or a longer ISI, which seems to allow the participants more independent processing of visual temporal judgments thus reducing their susceptibility to interference.

Chapter 6 –

SUMMARY and CONCLUSIONS

The overall aim of this research was to investigate how modality and spatial presentation can influence visual and auditory duration judgements in the millisecond range. One of the main objectives was to shed light on the interactions between space and time, focusing on right and left presentation of visual and auditory stimuli in tasks with presentation of either mixed or blocked modality trials.

The empirical background for our study was provided by recent findings suggesting a tendency for overestimations of durations presented on the right side of visual space and underestimations of durations presented on the left (Oliveri, Koch & Caltagirone, 2009). However, this effect of right/left spatial presentation has not been previously studied in the auditory duration judgments. Sensory modality (visual versus auditory) has been found to be a major determiner of the perceived duration of stimuli. Apart from the common finding that auditory temporal judgments are more precise than visual ones, visual stimuli are often perceived as shorter than auditory stimuli of equal physical duration (Droit-Volet, Meck & Penney, 2007). The exact circumstances under which these modality differences occur are not yet clear. Finally, a central debate in the temporal perception literature concerns the mechanisms that underlie temporal processing of different modalities: is there a central temporal mechanism or distinct, modality specific mechanisms? Similar effects of the spatial location of presentation on visual and auditory time judgments would support the existence of a central, amodal mechanism whereas diverse effects within visual and auditory domains would provide evidence for distinct mechanisms.

The above questions were addressed in the present thesis in a series of experiments based on the duration discrimination paradigm – a well established task in time perception studies, whereby participants are presented with two brief stimuli (circles or tones) in sequence and required to judge whether the second stimulus was longer or shorter in duration than the first. Stimuli were presented on the right or left side of the screen (and to the right or left ear) in the experiments of Chapters 3 and 5 and on the top or bottom side of the screen in the experiments that were presented in Chapter 4. The second stimuli were presented either at the same or different location as the standard. No effect of location (right versus left or top versus bottom) was observed in any experiment, a finding that calls into question the static influence of positioning per se on temporal judgments.

However, an effect of change of location was found: in the experiments where participants were exposed to visual and auditory trials within the same session (Experiments 2, 3, 5 & 6), in visual conditions participants overestimated the durations when the comparison stimulus appeared at a different location to the standard. In the change of location conditions, visual judgments were also judged longer than the auditory ones, a finding that initially seemed to be inconsistent with previously reported effects of modality on perceived durations (shorter judgments of visual stimuli compared to auditory when presented within the same session). It is suggested that this overestimation is the result of a mechanism that compensates for the loss of time that occurs during spatial attention shifts between the two different locations, by adding a specific duration. In the visual trials of the blocked conditions (where there are no interspersed auditory trials), this mechanism works seamlessly to accurately compensate for the lost duration, and so is not noticeable. However, when

visual and auditory trials are intermixed, the mechanism is over-activated, resulting in an overestimation and overcorrection of the error, thus resulting in a systematic bias. This bias is attributed to an automatic crossmodal combination or comparison of the visual and auditory stimuli. This automatic integration of visual and auditory temporal information seems to take place only for small ISIs. When, in contrast, a longer ISI is used in Experiment 8, the overestimation bias disappears suggesting that in this case visual temporal processing occurs independently of the auditory temporal processing.

Furthermore, an underestimation of same location visual trials was manifested across all experiments involving this location condition (Experiments 3, 4, 6, 7 & 8). Different hypotheses for the mechanisms underlying this effect were discussed, based either in centralized timing mechanism accounts, or more localised temporal processing accounts. Lower levels of attention dedicated to the same location conditions compared to the change of location conditions were suggested to be a potential interpretation of the results. Alternatively, it could be the result of comparing the output of one "clock" (temporal mechanism) – same location conditions – to the outputs of two different "clocks" (temporal mechanisms) – change of location conditions. In contrast to the overestimation bias, the underestimation of same location conditions manifested in both experiments that used either mixed modality presentation or single visual modality presentation. This underestimation bias was smaller in the mixed modality experiments (3 & 6) – where overestimation of change of location trials was found – than in the single visual modality experiments or the longer ISI experiment (4, 7 & 8). The two effects (underestimation of same location and overestimation of change of location) were

found to be negatively correlated, suggesting that when the automatic crossmodal combination takes place it may affect both *change of location* and *same location* conditions, resulting in an overestimation of the former and a decrease of the underestimation bias of the latter. In experiments where only visual modality trials are presented, such as 4 & 7, the overestimation bias disappears and the underestimation is more prominent. This finding suggests that overestimation and underestimation biases are caused by two separate mechanisms, which combine in cases of modality mixing.

In contrast to visual judgments, the auditory duration judgments were not affected by any of the manipulations. This differential pattern of performance in visual and auditory domains supports the existence of separate, modality specific temporal processing mechanisms. Neither the side of the ear from which sounds were presented, nor the type of modality presentation (mixed versus single) affected auditory duration discrimination in any of the measures with one exception: reaction time performance. In mixed modality presentation experiments – independently of the number of location conditions – participants were slower in auditory compared to visual duration judgments. This unexpected finding was attributed to differential strategies adopted for the two modalities: as the visual duration task is quite difficult and the capacity of visual sensory memory is more restricted, participants tend to give up and so reply faster without taking time for consideration; in contrast, auditory memory has greater temporal capacity and as a result there is more time available to improve the judgments and that leads to longer reaction times.

The results of the present thesis have important implications for the contemporary models of time perception, particularly the involvement of spatial location in temporal processing. Our experiments did not support the hypothesis of a spatial representation of time through a laterally oriented line, since no location was found to differ from any other. However, they gave strong evidence for the role of change or consistency of visual stimuli location in brief duration judgments. This observation substantiates the hypothesis that dynamic spatial attention is a more important factor in temporal awareness than static spatial location.

Very few recent studies have emphasized the role of location change on temporal perception. Cicchini & Morrone (2009) reported a compression of duration when participants had to perform two concurrent visual tasks (a duration task and a non-temporal task). This compression was apparent only for empty intervals marked by stimuli appearing in different locations. Additionally, selectivity of temporal mechanisms on spatial position has been reported in motion adaptation studies (Johnston et al., 2006). The present study is the first to report a clear effect of *change of location* on duration judgments of filled visual stimuli, in the absence of a concurrent task. This finding supports the notion of location-specific temporal processing, via the interpretation that the effect arises due to the process of integrating temporal data associated with distinct spatial locations (consistent with the Cicchini & Morrone's (2009) findings).

A notable finding of the present thesis is the implied presence of an error-correction mechanism as an essential feature of spatio-temporal awareness. This mechanism facilitates the relatively accurate duration discrimination observed in the visual change of location conditions, by correcting for the loss of time induced by

spatial attention shifts. However, this mechanism is only revealed in cases of mixed visual and auditory presentation, where it is over-activated, resulting into a systematic bias. It is suggested that this bias provides evidence for an automatic interaction between visual and auditory duration representations, which causes interference. This crossmodal comparison seems to be facilitated by the short ISI; when the ISI is longer, there is more time for different modal representations to be processed separately, and so the bias disappears. Therefore the present findings implicate separate low-level temporal mechanisms for the different modalities as well as separate processing of temporal features at different points in visual space. The unified and coherent experience of time emerges from the integration of these modally and spatially distinct temporal mechanisms.

The present evidence for integration of these separate mechanisms is highly significant for intrinsic models of timing. As mentioned in Chapter 1, a central criticism of intrinsic temporal models, such as SDN, is that they are highly susceptible to noise and thus they cannot adequately explain the general precision of temporal judgments. Accordingly, the operation of more generic representation mechanisms, allowing the comparison/integration between different channels, has been suggested as a solution to this problem (Buonomano, Bramen & Khodadadifar, 2009). The present results expand these models by offering behavioural evidence for the nature of the integration of the separate channels.

The results of the present thesis also contribute to our understanding of the modality effects on temporal processing and particularly on the visual – auditory differences in perceived duration; the data demonstrate that the widely observed modality effect on subjective duration – “lights are judged as shorter than sounds” –

can even be reversed if the visual stimuli are presented in separate locations. Thus, when change of location is involved and the ISI is short, overestimation of visual trials can be observed. In contrast, when the ISI is longer, more independent processing of visual intervals takes place and therefore, the bias disappears. The presently discovered role of the ISI in modality differences in subjective duration has notable implications, which should be taken into account by future studies exploring visual/auditory differences in time perception.

The experiments presented here inevitably have limitations. One inherent limitation of these studies is the location manipulation in the auditory domain. Monaural presentation of sounds might not have been the most appropriate way of presenting auditory intervals, which may explain the absence of noticeable effects of location on auditory duration judgments. Future studies could instead use external speakers in order to vary the location of sound, thus producing a spatial manipulation which is more similar to that experienced in the visual condition, and which has previously been used in studies demonstrating the temporal ventriloquist effect (Burr, Banks & Morrone, 2009).

Moreover, the fact that only one standard duration (300 ms) was used across all experiments restricts the interpretation of the results as it does not allow us to check whether the observed effects were constant or proportional to the duration of the standard stimulus. As the number of independent variables was already quite large, we decided to keep the standard duration constant. However, in future studies it would be worth exploring the effect of various standard durations. The nature of the effect could be informative as to the nature of the underlying mechanisms; for

instance in previous studies a proportional effect was taken as an indication of a difference between “clock” speeds, whereas a constant effect as a suggestion for an account based on the alteration of the temporal onset of stimuli.

The present thesis focused on the temporal performance of individuals with intact processing of visual and auditory temporal information. The results of this study corroborate previous findings on the dominance of the auditory modality for temporal processing. A further research question inspired by the present work is: how does temporal processing differ in individuals deprived of auditory input either congenitally or from an early age (deaf individuals)? Very few previous studies have examined temporal processing in deaf participants. A relatively recent study examined the performance of congenitally deaf adolescents in production and reproduction of durations at the minute range (Kowalska, & Szelag, 2006). To our knowledge no investigators have examined the differences between deaf and hearing individuals in duration comparison. Thus, how temporal processing works in deaf individuals seems to be an interesting follow up of the current study.

Finally, the present thesis provided a behavioural framework, which in future could be applied to addressing the neural basis of temporal processing. As was mentioned in Chapter 1, multiple neural systems are involved in timing, depending on the task, stimulus modality, duration range etc. (Wiener, Matell & Coslett, 2011). Although distinct brain areas and local neural structures have been associated with different aspects of temporal processing, certain areas – such as the cerebellum – have been found to be activated independently of task and stimulus type. These areas

are plausible candidates for the integration of temporal information from different channels with our work offering the experimental basis for it.

To conclude, this work contributes new insights to the literature on millisecond temporal processing and the underlying cognitive mechanisms. In particular the present work has shed new light on the possible mechanisms by which temporal awareness arises from visual, auditory and spatial cognitive processes. We hope that this research will open up new perspectives in the investigation of temporal processing and will help to advance and extend the current models of time processing.

REFERENCES

Alexander, I., Cowey, A., & Walsh, V. (2005). The right parietal cortex and time perception: Back to Critchley and the Zeitraffer phenomenon. *Cognitive Neuropsychology*, *22*(3/4), 306–315. (doi:10.1080/02643290442000356)

Arao, H., Suetomi, D., & Nakajima, Y. (2000). Does time-shrinking take place in visual temporal patterns. *Perception*, *29*(7), 819–830.

Ayhan, I., Bruno, A., Nishida, S., & Johnston, A. (2009). The spatial tuning of adaptation-based time compression. *Journal of Vision*, *9*(11), 2.1–12. (doi:10.1167/9.11.2)

Ayhan, I., Bruno, A., Nishida, S., & Johnston, A. (2011). Effect of the luminance signal on adaptation-based time compression. *Journal of Vision*, *11*(7), 1–17. (doi:10.1167/11.7.22)

Basso, G., Nichelli, P., Frassinetti, F., & di Pellegrino, G. (2006). Time perception in a neglected space. *Neuroreport*, *7*(13), 2111–2114.

Battelli, L., Pascual-Leone, A., & Cavanagh, P. (2007). The "when" pathway of the right parietal lobe. *Trends in cognitive sciences*, *11*(5), 204–210. (doi:10.1016/j.tics.2007.03.001)

Binda, P., Morrone, M. C., Ross, J., & Burr, D. C. (2011). Underestimation of perceived number at the time of saccades. *Vision Research*, *51*(1), 34–42. (doi:10.1016/j.visres.2010.09.028)

Block, R. A., & Zakay, D. (1996). Models of psychological time revisited. In H. Helfrich (Ed.), *Time and mind* (pp. 171–195). Kirkland: Hogrefe & Huber.

Block, R. A., Hancock, P. A., & Zakay, D. (2010). How cognitive load affects duration judgments: A meta-analytic review. *Acta Psychologica*, *134*(3), 330–343. (doi:10.1016/j.actpsy.2010.03.006)

Brannon, E. M., Libertus, M. E., Meck, W. H., & Woldorff, M. G. (2008). Electrophysiological measures of time processing in infant and adult brains: Weber's law holds. *Journal of Cognitive Neuroscience*, *20*(2), 193–203.

Brown, S. W. (1985). Time perception and attention: The effects of prospective versus retrospective paradigms and task demands on perceived duration. *Perception & Psychophysics*, *38*(2), 115–124.

Brown, S. W. (2008). The attenuation effect in timing: Counteracting dual-task interference with time-judgment skill training. *Perception*, *37*(5), 712–724. (doi:10.1068/p5698)

Brown, S. W. (2010). Timing, resources, and interference: attentional modulation of time perception. In A. C. Nobre, & J. T. Coull (Ed.), *Attention and time* (pp. 107-122). Oxford: Oxford University Press.

Brown, S. W., & Boltz, M. G. (2002). Attentional processes in time perception: effects of mental workload and event structure. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(3), 600–615. (doi:10.1037//0096-1523.28.3.600)

Bruno, A., Ayhan, I., & Johnston, A. (2010). Retinotopic adaptation-based visual duration compression. *Journal of Vision*, *10*(10), 30. (doi:10.1167/10.10.30)

Bueti, D., & Macaluso, E. (2011). Physiological correlates of subjective time: evidence for the temporal accumulator hypothesis. *NeuroImage*, *57*(3), 1251–1263. (doi:10.1016/j.neuroimage.2011.05.014)

Bueti, D., Bahrami, B., & Walsh, V. (2008a). Sensory and association cortex in time perception. *Journal of Cognitive Neuroscience*, *20*(6), 1054–1062.

Bueti, D., Walsh, V., Frith, C., & Rees, G. (2008b). Different brain circuits underlie motor and perceptual representations of temporal intervals. *Journal of Cognitive Neuroscience*, *20*(2), 204–214. (doi:10.1162/jocn.2008.20017)

Buhusi, C. V., & Meck, W. H. (2005). What makes us tick? Functional and neural mechanisms of interval timing *Nature reviews. Neuroscience*, *6*(10), 755–765. (doi:10.1038/nrn1764)

Buonomano, D. V., & Maass, W. (2009). State-dependent computations: spatiotemporal processing in cortical networks. *Nature reviews. Neuroscience*, *10*(2), 113–125. (doi:10.1038/nrn2558)

Buonomano, D. V., Bramen, J., & Khodadadifar, M. (2009). Influence of the interstimulus interval on temporal processing and learning: testing the state-dependent network model. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1525), 1865–1873. (doi:10.1098/rstb.2009.0019)

Burle, B., & Casini, L. (2001). Dissociation between activation and attention effects in time estimation: Implications for internal clock models. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(1), 195–205. (doi:10.1037/0096-1523.27.1.195)

Burr, D. C., Cicchini, G. M., Arrighi, R., & Morrone, M. C. (2011). Spatiotopic selectivity of adaptation-based compression of event duration. *Journal of Vision*, *11*(2), 21, 1–9. (doi:10.1167/11.2.21)

Burr, D., & Alais, D. (2006). Combining visual and auditory information. *Progress in Brain Research*, *155*, 243–258.

Burr, D., & Morrone, C. (2006). Time perception: space–time in the brain. *Current Biology*, *16*(5), R171–R173.

Burr, D., Banks, M. S., & Morrone, M. C. (2009). Auditory dominance over vision in the perception of interval duration. *Experimental Brain Research*, *198*(1), 49–57. (doi:10.1007/s00221-009-1933-z)

Burr, D., Tozzi, A., & Morrone, M. C. (2007). Neural mechanisms for timing visual events are spatially selective in real-world coordinates. *Nature Neuroscience*, *10*(4), 423–425. (doi:10.1038/nn1874)

Calabria, M., Jacquin-Courtois, S., Miozzo, A., Rossetti, Y., Padovani, A., Cotelli, M., & Miniussi, C. (2011). Time perception in spatial neglect: A distorted representation. *Neuropsychology*, *25*(2), 193–200. (doi:10.1037/a0021304)

Carrasco, M. (2006). Covert attention increases contrast sensitivity: Psychophysical, neurophysiological and neuroimaging studies. *Progress in Brain Research*, *154*, 33–70. (doi:10.1016/S0079-6123(06)54003-8)

Carrasco, M., Ling, S., & Read, S. (2004). Attention alters appearance. *Nature Neuroscience*, *7*(3), 308–313. (doi:10.1038/nn1194)

Casasanto, D., & Boroditsky, L. (2008). Time in the mind: using space to think about time. *Cognition*, *106*(2), 579–593. (doi:10.1016/j.cognition.2007.03.004)

Casini, L., & Macar, F. (1997). Effects of attention manipulation on judgments of duration and of intensity in the visual modality. *Memory & Cognition*, *25*(6), 812–818.

Casini, L., & Vidal, F. (2011). The SMAs: Neural Substrate of the Temporal Accumulator. *Frontiers in integrative neuroscience*, *5*(35), 1–3. (doi:10.3389/fnint.2011.00035)

Chen, K.-M., & Yeh, S.-L. (2009). Asymmetric cross-modal effects in time perception. *Acta Psychologica*, *130*(3), 225–234. (doi:10.1016/j.actpsy.2008.12.008)

Chen, Y., Huang, X., Luo, Y., Peng, C., & Liu, C. (2010). Differences in the neural basis of automatic auditory and visual time perception: ERP evidence from an across-modal delayed response oddball task. *Brain research*, *1325*, 100–111. (doi:10.1016/j.brainres.2010.02.040)

Chen, Z., & O'Neill, P. (2001). Processing demand modulates the effect of spatial attention on the judged duration of a brief stimulus. *Perception & Psychophysics*, *63*, 1229–1238.

Cicchini, G. M., & Morrone, M. C. (2009). Shifts in spatial attention affect the perceived duration of events. *Journal of Vision*, *9*(1), 1–13. (doi:10.1167/9.1.9)

Cordes, S., Williams, C. L., & Meck, W. H. (2007). Common representations of abstract quantities. *Current Directions in Psychological Science*, *16*(3), 156–161.

Correa, A., & Nobre, A. C. (2008). Spatial and temporal acuity of visual perception can be enhanced selectively by attentional set. *Experimental Brain Research*, *189*(3), 339–344. (doi:10.1007/s00221-008-1429-2)

Coull, J. T., Cheng, R.-K., & Meck, W. H. (2011). Neuroanatomical and neurochemical substrates of timing. *Neuropsychopharmacology : official publication of the American College of Neuropsychopharmacology*, *36*(1), 3–25. (doi:10.1038/npp.2010.113)

Coull, J. T., Vidal, F., Nazarian, B., & Macar, F. (2004). Functional anatomy of the attentional modulation of time estimation *Science (New York, N.Y.)*, *303*(5663), 1506–1508. (doi:10.1126/science.1091573)

Danckert, J., Ferber, S., Pun, C., Broderick, C., Striemer, C., Rock, S., & Stewart, D. (2007). Neglected time: impaired temporal perception of multisecond intervals in unilateral neglect. *Journal of Cognitive Neuroscience*, *19*(10), 1706–1720. (doi:10.1162/jocn.2007.19.10.1706)

Droit-Volet, S., & Rattat, A.-C. (2007). A further analysis of time bisection behavior in children with and without reference memory: The similarity and the partition task. *Acta Psychologica*, *125*(2), 240–256. (doi:10.1016/j.actpsy.2006.08.003)

Droit-Volet, S., & Wearden, John. (2002). Speeding up an internal clock in children? Effects of visual flicker on subjective duration. *Quarterly Journal of Experimental Psychology Section B*, *55*(3), 193–211. (doi:10.1080/02724990143000252)

Droit-Volet, S., Clément, A., & Fayol, M. (2008). Time, number and length: Similarities and differences in discrimination in adults and children. *The Quarterly Journal of Experimental Psychology*, *61*(12), 1827–1846.

Droit-Volet, S., Meck, W. H., & Penney, T. B. (2007). Sensory modality and time perception in children and adults. *Behavioural Processes*, *74*(2), 244–250. (doi:10.1016/j.beproc.2006.09.012)

Droit-Volet, S., Tourret, S., & Wearden, John. (2004). Perception of the duration of auditory and visual stimuli in children and adults. *The Quarterly Journal of Experimental Psychology Section A*, *57*(5), 797–818. (doi:10.1080/02724980343000495)

Eagleman, D. M. (2008). Human time perception and its illusions. *Current opinion in neurobiology*, *18*(2), 131–136. (doi:10.1016/j.conb.2008.06.002)

Eagleman, D. M., & Pariyadath, V. (2009). Is subjective duration a signature of coding efficiency. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1525), 1841–1851. (doi:10.1098/rstb.2009.0026)

Eagleman, D. M., Tse, P. U., Buonomano, D., Janssen, P., Nobre, A. C., & Holcombe, A. O. (2005). Time and the brain: how subjective time relates to neural time. *The Journal of Neuroscience*, *25*(45), 10369–10371. (doi:10.1523/JNEUROSCI.3487-05.2005)

Frassinetti, F., Magnani, B., & Oliveri, M. (2009). Prismatic lenses shift time perception. *Psycholical Science*, *20*(8), 949–954. (doi:10.1111/j.1467-9280.2009.02390.x)

Georg, K., & Lappe, M. (2007). Spatio-temporal contingency of saccade-induced chronostasis. *Experimental Brain Research*, *180*(3), 535–539. (doi:10.1007/s00221-007-0876-5)

Gibbon, J. (1977). Scalar expectancy theory and Weber's law in animal timing. *Psychological Review*, *84*(3), 279–325. American Psychological Association. (doi:10.1037/0033-295X.84.3.279)

Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences*, *423*, 52–77.

Gooch, C. M., Wiener, M., Wencil, E. B., & Coslett, H. B. (2010). Interval timing disruptions in subjects with cerebellar lesions. *Neuropsychologia*, *48*(4), 1022–1031. (doi:10.1016/j.neuropsychologia.2009.11.028)

Grondin, S. (1993). Duration discrimination of empty and filled intervals marked by auditory and visual signals. *Perception & Psychophysics*, *54*(3), 383–394.

Grondin, S. (2010). Timing and time perception: a review of recent behavioral and neuroscience findings and theoretical directions. *Attention Perception & Psychophysics*, *72*(3), 561–582. (doi:10.3758/APP.72.3.561)

Grondin, S., & Plourde, M. (2007). Discrimination of time intervals presented in sequences: spatial effects with multiple auditory sources. *Human movement science*, *26*(5), 702–716. (doi:10.1016/j.humov.2007.07.009)

Guttman, S. E., Gilroy, L. A., & Blake, R. (2005). Hearing what the eyes see: auditory encoding of visual temporal sequences. *Psychological science*, *16*(3), 228–235. (doi:10.1111/j.0956-7976.2005.00808.x)

Guyau, J. (1890). *La genèse de l'idée de temps*. Paris: Alcan.

Harrington, D., Haaland, K., & Knight, R. (1998). Cortical networks underlying mechanisms of time perception. *The Journal of Neuroscience*, *18*(3), 1085–1095.

Hein, E., Rolke, B., & Ulrich, R. (2006). Visual attention and temporal discrimination: Differential effects of automatic and voluntary cueing. *Visual Cognition*, *13*(1), 29–50.

Hodinott-Hill, I., Thilo, K. V., Cowey, A., & Walsh, V. (2002). Auditory Chronostasis. Hanging on the Telephone. *Current Biology*, *12*, 1779–1781.

Ivry, R. B., & Schlerf, J. E. (2008). Dedicated and intrinsic models of time perception. *Trends in cognitive sciences*, *12*(7), 273–280.

Ivry, R. B., & Spencer, R. M. (2004). The neural representation of time. *Current opinion in neurobiology*, *14*(2), 225–232. (doi:10.1016/j.conb.2004.03.013)

Jäncke, L., Loose, R., Lutz, K., Specht, K., & Shah, N. J. (2000). Cortical activations during paced finger-tapping applying visual and auditory pacing stimuli. *Cognitive Brain Research*, *10*, 51–66.

Johnston, A. (2010). Modulation of time perception by visual adaptation. In A.C. Nobre & J. T. Coull (Eds.), *Attention and Time* (pp. 187–200). Oxford: Oxford University Press.

Johnston, A., Arnold, D. H., & Nishida, S. (2006). Spatially Localized Distortions of Event Time. *Current Biology*, *16*(5), 472–479. (doi:10.1016/j.cub.2006.01.032)

Johnston, A., Bruno, A., & Ayhan, I. (2011). Retinotopic selectivity of adaptation-based compression of event duration: Reply to Burr, Cicchini, Arrighi, and Morrone. *Journal of Vision*, *11*(2), 21a, 1–3. (doi:10.1167/11.2.21a)

Kanabus, M., Szelag, E., Rojek, E., & Poppel, E. (2002). Temporal order judgement for auditory and visual stimuli. *Acta Neurobiologiae Experimentalis*, *62*(4), 263–270.

Kanai, R., & Watanabe, M. (2006). Visual onset expands subjective time. *Perception & Psychophysics*, *68*(7), 1113–1123
.

Karmarkar, U. R. (2011). Defining the contributions of network clock models to millisecond timing. *Frontiers in integrative neuroscience*, *5*(41), 1–2. (doi:10.3389/fnint.2011.00041)

Karmarkar, U. R., & Buonomano, D. V. (2007). Timing in the Absence of Clocks: Encoding Time in Neural Network States. *Neuron*, *53*(3), 427–438. (doi:10.1016/j.neuron.2007.01.006)

Klink, P. C., Montijn, J. S., & van Wezel, R. J. A. (2011). Crossmodal duration perception involves perceptual grouping, temporal ventriloquism, and variable internal clock rates. *Attention Perception & Psychophysics*, *73*(1), 219–236. (doi:10.3758/s13414-010-0010-9)

Koch, G., Oliveri, M., & Caltagirone, C. (2009). Neural networks engaged in milliseconds and seconds time processing: evidence from transcranial magnetic stimulation and patients with cortical or subcortical dysfunction. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1525), 1907–1918. (doi:10.1098/rstb.2009.0018)

Koch, G., Oliveri, M., Carlesimo, G. A., & Caltagirone, C. (2002). Selective deficit of time perception in a patient with right prefrontal cortex lesion. *Neurology*, *59*(10), 1658–1659.

Kohn, A. (2007). Visual adaptation: physiology, mechanisms, and functional benefits. *Journal of neurophysiology*, *97*(5), 3155–3164. (doi:10.1152/jn.00086.2007)

Kowalska, J., & Szelag, E. (2006). The effect of congenital deafness on duration judgment. *Journal of Child Psychology and Psychiatr*y, *47*(9), 946–953. (doi:10.1111/j.1469-7610.2006.01591.x)

Lapid, E., Ulrich, R., & Rammsayer, T. (2008). On estimating the difference limen in duration discrimination tasks: A comparison of the 2AFC and the reminder task. *Perception & Psychophysics*, *70*(2), 291–305. (doi:10.3758/PP.70.2.291)

Lapid, E., Ulrich, R., & Rammsayer, T. (2009). Perceptual learning in auditory temporal discrimination: no evidence for a cross-modal transfer to the visual modality. *Psychonomic bulletin & review*, *16*(2), 382–389. (doi:10.3758/PBR.16.2.382)

Lejeune, H., & Wearden, J H. (2009). Vierordt's The Experimental Study of the Time Sense(1868) and its legacy. *European Journal of Cognitive Psychology*, *21*(6), 941–960. (doi:10.1080/09541440802453006)

Lewis, P. A., & Miall, R. C. (2003a). Brain activation patterns during measurement of sub- and supra-second intervals. *Neuropsychologia*, *41*(12), 1583–1592. (doi:10.1016/S0028-3932(03)00118-0)

Lewis, P. A., & Miall, R. C. (2003b). Distinct systems for automatic and cognitively controlled time measurement: evidence from neuroimaging. *Current opinion in neurobiology*, *13*(2), 250–255. (doi:10.1016/S0959-4388(03)00036-9)

Lewis, P. A., & Miall, R. C. (2006). Remembering the time: a continuous clock *Trends in cognitive sciences*, *10*(9), 401–406. (doi:10.1016/j.tics.2006.07.006)

Macar, F., Grondin, S., & Casini, L. (1994). Controlled attention sharing influences. *Memory & Cognition*, *22*(6), 673–686.

Macar, F., Lejeune, H., Bonnet, M., Ferrara, A., Pouthas, V., Vidal, F., & Maquet, P. (2002). Activation of the supplementary motor area and of attentional networks during temporal processing. *Experimental Brain Research*, *142*(4), 475–485. (doi:10.1007/s00221-001-0953-0)

Mamassian, P., & Landy, M. S. (2010). It's that time again. *Nature Neuroscience*, *13*(8), 914–916. (doi:10.1038/nn0810-914)

Mapelli, D., Rusconi, E., & Umiltà, C. (2003). The SNARC effect: an instance of the Simon effect *Cognition*, *88*(3), B1–B10. (doi:10.1016/S0010-0277(03)00042-8)

Mattes, S., & Ulrich, R. (1998). Directed attention prolongs the perceived duration of a brief stimulus. *Perception & Psychophysics*, *60*(8), 1305–1317.

Mella, N., Conty, L., & Pouthas, V. (2011). The role of physiological arousal in time perception: psychophysiological evidence from an emotion regulation paradigm. *Brain and cognition*, *75*, 182–187.

Mohl, W., & Pfurtscheller, G. (1991). The role of the right parietal region in a movement time estimation task. *Neuroreport*, *2*(6), 309–312.

Morrone, C., & Burr, D. (2010). Space-time in the brain. In A. C. Nobre & J. T. Coull (Eds.), *Attention and Time* (pp. 177–186). Oxford: Oxford Universtiy Press.

Morrone, M. C., Ross, J., & Burr, D. (2005). Saccadic eye movements cause compression of time as well as space. *Nature Neuroscience*, *8*(7), 950–954. (doi:10.1038/nn1488)

Murray, M. M., De Santis, L., Thut, G., & Wylie, G. R. (2009). The costs of crossing paths and switching tasks between audition and vision. *Brain and cognition*, *69*(1), 47–55. (doi:10.1016/j.bandc.2008.05.004)

N'Diaye, K., Ragot, R., Garnero, L., & Pouthas, V. (2004). What is common to brain activity evoked by the perception of visual and auditory filled durations? A study with MEG and EEG co-recordings. *Cognitive Brain Research*, *21*(2), 250–268. (doi:10.1016/j.cogbrainres.2004.04.006)

Nagarajan, S. S., Blake, D. T., Wright, B. A., Byl, N., & Merzenich, M. M. (1998). Practice-related improvements in somatosensory interval discrimination are temporally specific but generalize across skin location, hemisphere, and modality. *The Journal of Neuroscience*, *18*(4), 1559–1570.

New, J. J., & Scholl, B. J. (2009). Subjective time dilation: Spatially local, object-based, or a global visual experience *Journal of Vision*, *9*(2), 1–11. (doi:10.1167/9.2.4)

Ogden, R. S., Wearden, John H, & Jones, L. A. (2010). Are memories for duration modality specific? *The Quarterly Journal of Experimental Psychology*, *63*(1), 65–80. (doi:10.1080/17470210902815422)

Oliveri, M., Koch, G., & Caltagirone, C. (2009). Spatial–temporal interactions in the human brain. *Experimental Brain Research*, *195*(4), 489–497. (doi:10.1007/s00221-009-1834-1)

Ortega, L., Lopez, F., & Church, R. M. (2009). Modality and intermittency effects on time estimation. *Behavioural Processes*, *81*(2), 270–273. (doi:10.1016/j.beproc.2009.02.009)

Park, J., Schlag-Rey, M., & Schlag, J. (2003). Voluntary action expands perceived duration of its sensory consequence. *Experimental Brain Research*, *149*(4), 527–529. (doi:10.1007/s00221-003-1376-x)

Penney, T. B., Gibbon, J., & Meck, W. H. (2000). Differential effects of auditory and visual signals on clock speed and temporal memory. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(6), 1770–1787. (doi:10.1037//0096-1523.26.6.1770)

Penton-Voak, I. S., Edwards, H., Percival, A., & Wearden, J H. (1996). Speeding Up an Internal Clock in Humans? Effects of Click Trains on Subjective Duration. *Journal of Experimental Psychology: Animal Behavior Processes*, *22*(3), 307–320.

Plummer, C., & Humphrey, N. (2008). Time perception in children with ADHD: the effects of task modality and duration. *Child Neuropsychology*, *15*(2), 147–162. (doi:10.1080/09297040802403690)

Pouthas, V., & Perbal, S. (2004). Time perception depends on accurate clock mechanisms as well as unimpaired attention and memory processes. *Acta Neurobiologiae Experimentalis*, *64*, 367–385.

Rammsayer, T. H. (2010). Differences in duration discrimination of filled and empty auditory intervals as a function of base duration. *Attention Perception & Psychophysics*, *72*(6), 1591–1600. (doi:10.3758/APP.72.6.1591)

Rammsayer, T. H., & Leutner, D. (1996). Temporal discrimination as a function of marker duration. *Perception & Psychophysics*, *58*(8), 1213–1223.

Rammsayer, T. H., & Lima, S. D. (1991). Duration discrimination of filled and empty auditory intervals: cognitive and perceptual factors. *Perception & Psychophysics*, *50*(6), 565–574.

Rao, S. M., Mayer, A. R., & Harrington, D. L. (2001). The evolution of brain activation during temporal processing. *Nature Neuroscience*, *4*(3), 317–323. (doi:10.1038/85191)

Sawyer, T. F., Meyers, P. J., & Huser, S. J. (1994). Contrasting task demands alter the perceived duration of brief time intervals. *Perception & Psychophysics*, *56*(6), 649–657.

Seifried, T., & Ulrich, R. (2010). Does the asymmetry effect inflate the temporal expansion of odd stimuli. *Psychological Research Psychologische Forschung*, *74*(1), 90–98. (doi:10.1007/s00426-008-0187-x)

Smith, J. G., Harper, D. N., Gittings, D., & Abernethy, D. (2007). The effect of Parkinson's disease on time estimation as a function of stimulus duration range and modality. *Brain and cognition*, *64*(2), 130–143. (doi:10.1016/j.bandc.2007.01.005)

Spencer, R. M. C., Karmarkar, U., & Ivry, R. B. (2009). Evaluating dedicated and intrinsic models of temporal encoding by varying context. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1525), 1853–1863. (doi:10.1098/rstb.2009.0024)

Thomas, E. A. C., & Weaver, W. B. (1975). Cognitive processing and time perception. *Perception & Psychophysics*, *17*(4), 363–367.

Tse, P. U. (2010). Attention underlies subjective temporal expansion. In A. C. Nobre & J. T. Coull (Ed.), *Attention and time* (pp. 137-150). Oxford: Oxford University Press.

Tse, P. U., Intriligator, J., Rivest, J., & Cavanagh, P. (2004). Attention and the subjective expansion of time. *Perception & Psychophysics*, *66*(7), 1171–1189.

Ulrich, R., Nitschke, J., & Rammsayer, T. (2006). Perceived duration of expected and unexpected stimuli. *Psychological Research*, *70*(2), 77–87. (doi:10.1007/s00426-004-0195-4)

Vallesi, A., Binns, M. A., & Shallice, T. (2008). An effect of spatial-temporal association of response codes: understanding the cognitive representations of time. *Cognition*, *107*(2), 501–527. (doi:10.1016/j.cognition.2007.10.011)

van Wassenhove, V., Buonomano, D. V., Shimojo, S., & Shams, L. (2008). Distortions of Subjective Time Perception Within and Across Senses. *PLoS ONE*, *3*(1), e1437. (doi:10.1371/journal.pone.0001437.g006)

Vicario, C. M., Caltagirone, C., & Oliveri, M. (2007). Optokinetic stimulation affects temporal estimation in healthy humans. *Brain and cognition*, *64*(1), 68–73. (doi:10.1016/j.bandc.2006.12.002)

Vicario, C. M., Pecoraro, P., Turriziani, P., Koch, G., Caltagirone, C., & Oliveri, M. (2008). Relativistic compression and expansion of experiential time in the left and right space. *PLoS ONE*, *3*(3), e1716. (doi:10.1371/journal.pone.0001716)

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in cognitive sciences*, *7*(11), 483–488.

Warm, J. S., Stutz, R. M., & Vassolo, P. A. (1975). Intermodal transfer in temporal discrimination. *Perception & Psychophysics*, *18*(4), 281–286.

Wearden, JH. (1991). Do humans possess an internal clock with scalar timing properties. *Learning and Motivation*, *22*, 59–83.

Wearden, JH. (1999). “Beyond the fields we know...”: exploring and developing scalar timing theory. *Behavioural Processes*, *45*, 3–21.

Wearden, J H. (2008). Detectability and criterion measures in temporal generalization. *Behavioural Processes*, *78*(3), 374–379. (doi:10.1016/j.beproc.2008.01.017)

Wearden, J H, & Bray, S. (2001). Scalar timing without reference memory? Episodic temporal generalization and bisection in humans. *The Quarterly Journal of Experimental Psychology B*, *54*(4), 289–309. (doi:10.1080/02724990042000173)

Wearden, J H, & Ferrara, A. (1993). Subjective shortening in humans' memory for stimulus duration. *Quarterly Journal of Experimental Psychology Section B*, *46*(2), 163–186.

Wearden, J H, Edwards, H., Fakhri, M., & Percival, A. (1998). Why "Sounds Are Judged Longer Than Lights“": Application of a Model of the Internal Clock in Humans. *The Quarterly Journal of Experimental Psychology Section B*, *51*(2), 97–120.

Wearden, J H, Parry, A., & Stamp, L. (2002). Is subjective shortening in human memory unique to time representations. *Quarterly Journal of Experimental Psychology Section B*, *55*(1), 1–25. (doi:10.1080/02724990143000108)

Wearden, J H, Todd, N. P. M., & Jones, L. A. (2006). When do auditory/visual differences in duration judgements occur. *The Quarterly Journal of Experimental Psychology*, *59*(10), 1709–1724. (doi:10.1080/17470210500314729)

Whelan, R. (2008). Effective analysis of reaction time data. *The Psychological Record, 58,* 475-482.

Wiener, M., Matell, M. S., & Coslett, H. B. (2011). Multiple Mechanisms for Temporal Processing. *Frontiers in integrative neuroscience*, *5*(31), 1–3. (doi:10.3389/fnint.2011.00031)

Wiener, M., Turkeltaub, P., & Coslett, H. B. (2010). The image of time: a voxel-wise meta-analysis. *NeuroImage*, *49*(2), 1728–1740. (doi:10.1016/j.neuroimage.2009.09.064)

Wittmann, M., & van Wassenhove, V. (2009). The experience of time: neural mechanisms and the interplay of emotion, cognition and embodiment. *Philosophical Transactions of the Royal Society B*, *364*(1525), 1809–1813

Yarrow, Kielan. (2010). Temporal dilation: the chronostasis illusion and spatial attention. In A. C. Nobre & J. T. Coull (Ed.), *Attention and time* (pp. 137-150). Oxford: Oxford University Press.

Yarrow, Kielan, Haggard, P., & Rothwell, J. C. (2004). Action, arousal, and subjective time. *Conscioussness and Cognition*, *13*(2), 373–390. (doi:10.1016/j.concog.2003.10.006)

Yarrow, Klelan, Haggard, P., Heal, R., Brown, P., & Rothwell, J. C. (2001). Illusory perceptions of space and time preserve cross-saccadic perceptual continuity. *Nature*, *414*, 302–305.

Yeshurun, Y., & Marom, G. (2008). Transient spatial attention and the perceived duration of brief visual events. *Visual Cognition*, *16*(6), 826–848.

Zakay, D. (1993). Time estimation methods--do they influence prospective duration estimates. *Perception*, *22*(1), 91–101.